DISSERTATION

Transfer of Nutrient and Harmful Elements from Soil to Rice and Health Risk Assessments for the Vietnamese Population

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Dedication

To my dearest parents,

who have given me the best things and sacrificed all their lives for my progress in study.

Abstract

Thuy Phuong Nguyen

"Transfer of nutrient and harmful elements from soil into rice and health risk assessments for Vietnamese population"

Main and trace element concentrations in paddy soils and corresponding rice plants collected along some transnational-river systems in Vietnam including Red River in the north and Mekong River in the south, and Huong River in the center were investigated to provide an insight into paddy soil characteristics and the element transfers into rice plant, and to assess chronic health risks by potentially harmful elements through rice consumption. The studied paddy soils have similar parent materials consisting of alluvial sediments deposited by inundation and irrigation. Most of the soils are not or only slightly affected by heavy metal(loid)s contamination from anthropogenic activities, except for Cd enrichment by the use of phosphate fertilizer. Elevated arsenic concentrations exceeding the allowable limit of agricultural soil (15 mg kg^{-1}), are found mostly in the northern and the central paddy soils (80%), but at fewer soils in the south (11%). These high concentrations are the result of natural processes related to redox reactions of As-rich sulfide and Fe-oxides/hydroxide phases. Some specific sites close to the river bank and near a fertilizer and chemical factory show a strong enrichment of heavy metals, resulting from industrial wastewater application.

Due to similar concentrations of elements in the parent material not polluted by human activities, many trace elements show extremely sharp correlations with each other, which can be arranged into groups. The correlations are mainly caused by variable concentrations of dilution by quartz, bio-opal and organic matter in the soil. These correlations can be used to assess if a soil sample is polluted by a certain element.

Soil parameters play an important role in the transferability of elements from soil to rice plant causing a large spread of transfer factors. Although the background concentrations of elements in areas are hardly distinguishable, differences in soil pH-value, the content of organic matter, Fe- and Mn-oxides/hydroxides and clay minerals as well as the fertilizer input are the main reasons for contrasting element concentrations in the rice grains of the three research areas. Particularly, the translocation of the potentially harmful elements As, Cd, and Mn shows intermediate to high transfer factors. In general, concentrations of most elements in the plant parts decrease in the order: shoot >> husk > grain. Exceptions are Ni, Mg, Zn, S, Cu,

Mo, and P, which are more easily transported to the grains due to their electrostatic repulsion at the negative cell wall charges or to their formation of soluble organic complexes.

Health risks of harmful elements intake from rice consumption are estimated by applying four approaches: (1) Tolerable Upper Intake Level (UL) of total daily consumption – data available for As, Cd, Co, Mn, Mo, Ni, Pb, Sb, and U; (2) allowable Maximum Concentration (MC) of rice - data for As, Cd, and Pb; (3) non-cancer risks (HI) - data for As, Cd, Co, Cu, Mn, Mo, Ni, and Pb; and (4) cancer risk (∑ILCR) - data for As and Pb. The mentioned elements are the riskiest pollutants in rice for the Vietnamese population. For the UL-guidelines, 14% of the total studied samples cause health risks of exposure to As, 32% to Cd, and 21% to Pb. In comparison with the MC-values, 4%, 3%, and 19% of the rice samples exceed these levels of As, Cd, and Pb respectively. Results of non-cancer risks and cancer risks exhibit that all rice grains have the HI-values and ∑ILCR-values surpassing their safe and acceptable thresholds. Manganese occupies the highest portion of HI-index and As is the most potential oral carcinogenic factor. People in the three studied areas are facing the different levels of intoxication risk by these elements. People living in the Red River and Huong River area suffer from higher hazard of As and Cd, but not of Pb. People in the Mekong area are additionally exposed to Pb in rice, 10-times more than in the other areas. To mitigate these health risks, controlling the soil pH-value is a simple way that needs to be considered first.

Acknowledgements

To come to the completion of my doctoral journey, in this precious moment I would like to express heartfelt thanks to wonderful people who have helped and supported me during the great years of my life in Germany.

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The last and most important, I would like to express my gratefulness to my beloved parents and family, who always encourage and lift me up whenever I was at a standstill and feel down. Their sacrifice gave me all the motivations to stay on track all the way and accomplish my work.

Thank you all!

Thuy Phuong Nguyen

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List of Abbreviation

AWD	: Alternate wetting and drying
DMA	: Dimethylarsinic acid
EFSA	: European Food Safety Authority
FAO	: Food and Agriculture Organization
ha	: hectares
HI	: chronic Hazard Index
IARC	: International Agency for Research on Cancer
ICP-MS	: Inductively Coupled Plasma - Mass Spectrometry
ICP-OES	: Inductively Coupled Plasma - Optical Emission Spectrometry
ILCR	: Incremental Lifetime Cancer Risk
∑ILCR	: Cumulative Cancer Risk
LOI	: Loss on Ignition
MC	: Maximum Concentration
MMA	: Monomethylarsonic acid
OM	: Organic matter
RDA	: Daily Recommended Dietary Allowances
ROL	: Radical Oxygen Loss
TF	: Transfer factor
THQ	: Target Hazard Quotient
UL	: Tolerable Upper Intake Level
USEPA	: United States Environmental Protection Agency
WHO	: World Health Organization
b.w.	: body weight
iAs	: inorganic arsenic
tAs	: total arsenic

Chapter 1

General introduction

General Introduction

Rice is the primary staple food for more than half the world's population, with Asia representing the largest rice producing and consuming region (FAO 2018, 2019). Since some years, it is known that rice may contain health relevant concentrations of As and Cd. To put this information into a scientific context, a systematic environmental geochemistry study has been performed for Vietnam. The purposes are to get the information about the concentrations of numerous elements in paddy soils and corresponding rice plants as well as to get an estimate of the intake of potentially harmful elements and their health relevance from rice consumption. Soil and corresponding rice samples were collected in the two largest rice-growing areas in Vietnam including Red River delta in the north and Mekong River delta in the south, in addition to a few samples at Huong River in the central area. Abundant water for irrigation and fertile alluvial sediments deposited in the large transboundary river systems of the Red River and Mekong River deliver nutrients for rice agriculture, but the irrigation water and annual inundations may also bring some harmful elements like As, Cd, Pb, and Mn into the rice fields. The Red River flows from Yunnan in Southwest China through northern Vietnam into the Gulf of Tonkin (South China Sea). Parent materials of paddy soils in this delta are mainly alluvial sediments of the Yunnan Plateau and the surrounding hills. The Mekong River originates in the Tibetan plateau, and flows through Myanmar, Laos, Thailand, Cambodia, and finally Vietnam before it disembogues into the South China Sea. Paddy soil materials in Mekong River area are composed of alluvial delta sediments delivered from the Tibetan Plateau and lower mountains along the river course. The parent material of the few investigated samples from the Huong River derives from Annamite Range of eastern Indochina or called Truong Son mountain chain, Vietnam. The river flows through Hue City before it discharges into the South China Sea.

Sources of contaminants in paddy fields can be anthropogenic inputs from mining and industrial activities in upstream areas, but also the local application of fertilizers (especially phosphates), agrochemicals (pesticides and herbicides), compost, sewage sludge, and manure leading to increasing levels of toxic elements in soils and plants. To determine the accumulation of contaminants through these sources, paddy soil and corresponding rice plant samples were collected in the three river areas. In addition, to assess the spatial and temporal effects of industrial activities, samples close to a brick factory, a fertilizer and chemical factory, and adjacent to the river outside dykes in the Red River area were analyzed.

Three publications of the most important results were planned: one paper is already published, two of them are under review:

- Paper 1: Nguyen T. P., Ruppert H., Pasold T., Sauer B. (2019). Harmful and nutrient elements in paddy soils and their transfer into rice grains (Oryza sativa) along two river systems in northern and central Vietnam. *Environ Geochem Health*, https://doi.org/10.1007/s10653-019-00333-3

- Paper 2: Nguyen T. P., Ruppert H., Pasold T., Sauer B. (2019). Paddy soil geochemistry, uptake of trace elements by rice grains (Oryza sativa) and resulting health risks in the Mekong River Delta, Vietnam. *Environ Geochem Health.* (Submitted manuscript)

- Paper 3: Nguyen T. P., Ruppert H., Pasold T., Sauer B. (2019). Transfer of nutrient and toxic elements from paddy soils into different parts of rice plants (Oryza Sativa) in Vietnam and resulting health risks for the population. *Environ Sci Pollut Res*. (Submitted manuscript)

1.1 Aim of the study

Some previous studies just evaluated local contamination of paddy soils and rice caused by mining, industrial and domestic activities in Vietnam (Huong et al. 2008; Phuong et al. 2010; Chu 2011; Vinh et al. 2012). There has not been a systematic research on paddy soil geochemistry for the main rice-producing areas in Vietnam and the element concentrations in corresponding rice plants. In addition, health risk assessment from rice consumption is very important for the population of Vietnam. Such studies are very relevant, because Vietnam is the world’s fifth largest rice producer (after China, India, Indonesia, and Bangladesh) and the third largest rice exporter (after India and Thailand) (FAO 2018, 2019).

The rice quality can be especially affected by potentially harmful elements, which are in dissolved and solid forms contained in irrigation water (Li et al. 2010; Perera et al. 2016; Nogawa et al. 2017). In addition, redox mechanisms in the soil pore water of paddy soils may lead to the release As and other critical elements into soil solution, facilitating their uptake into rice plant. Paddy soils using water sources from corresponding transboundary river systems for irrigation demand have the potential to be enriched by many various outputs. All headwater activities may become a toxic element contamination/enrichment source for downstream soils, plants, and animals through river-transported materials that this was reported around the world (Garbarino et al 1995; Li et al. 2010; Perera et al. 2016; Nogawa et al. 2017; Singh et al. 2017, Bonotto et al. 2018). In addition, exhaust gases and wastewater from industrial actions, agrochemicals from agricultural practices can be disseminated and accumulated in paddy soils.

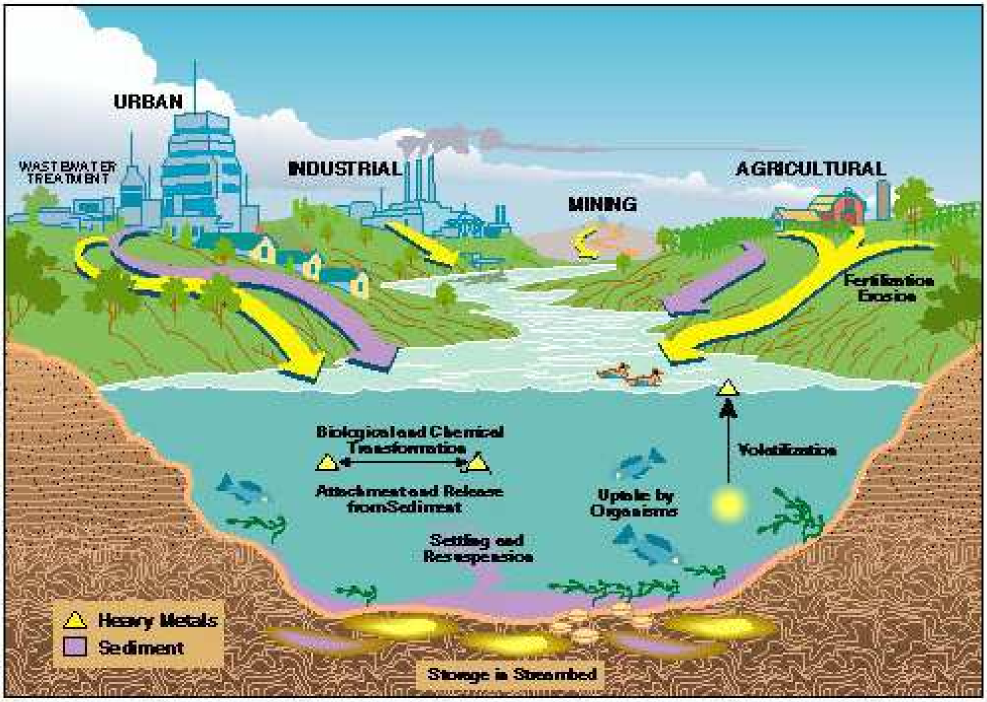


Fig. 1.1 Sources and sinks of heavy metals (*Garbarino et al. 1995*)

Allowable threshold values for the intake of some harmful elements are proposed by the World Health Organization and the Food and Agriculture Organization (WHO/FAO) and European Food Safety Authority (EFSA) organization. The intake of these elements by eating rice is calculated and compared with threshold values to estimate latent health risks posed to society. The daily intake of harmful element only by rice consumption may surpass the tolerable upper intake level of harmful element regulated for all sources (food and drinking water). However, the various approaches to Vietnamese health risk estimations lead to some discrepancies which are discussed in the three papers of this study. They accentuate the need for coherent and consistent guidelines on rice consumption relating to the community health risks.

To summarize, the main aims of this study are:

- to quantify paddy soil geochemistry for large rice-growing deltas in Vietnam,
- to estimate the enrichment of harmful elements in paddy fields by river-transported pollutants and local inputs,

- to calculate the physiological element concentrations which are corrected for adhering particles, and their transfer factors to rice grains and other plant parts like shoot, husk, and the total above-ground rice plant,
- to get information on the influence of main soil factors like pH, organic matter, clay minerals, Fe- and Mn-oxides/hydroxides on the element concentration and transferability from soil into rice plant,
- to assess the daily and chronic health risks of the local population by potentially harmful elements from rice consumption.

1.2 Basic facts related to this study

1.2.1 Research area

Located on the Indochina peninsula in Southeast Asia, Vietnam is an agricultural country with 94.6 million people in 2018, sharing 1.26% of the world population (Vietnam Government 2018). About 34.9% of the population live in urban areas and 65.1% in rural areas where many people depend on agricultural production.

Vietnam spans over nearly 15^{o} of latitude. It is located in the center of two main tropical monsoon areas (South-West Asian and East Asian monsoons) with seasonal reversals in atmospheric circulation and precipitation associated with the thermal contrast of land–sea heating (Nguyen et al. 2014). Vietnam’s climate varies significantly between the regions and seasons. In summer (April/May to October/November), the climate is dominated by the South-West monsoon, which is hot and wet especially in the southern part of Vietnam. In winter (November to March), the climate is affected by the East Asian monsoon which is cold and dry especially in the northern and the central areas. The average yearly precipitation is 1820 mm, varying from average an average 1600 to 2200 in the midlands and plains and 2000 to 2500 in the mountainous areas with an all over spread between 650 and 4760 mm (FAO 2012). The rainy season contributes to more than 80 % of yearly rainfall (Nguyen et al. 2014). In Ho Chi Minh City in southern Vietnam, the temperature is nearly stable at a yearly average of around 27°C, with average maximum temperature of 35°C in April (Climate-Data.org 2019). In the city of Hue in central Vietnam, the average winter temperature is 21 °C in January and the average summer temperature in June to August is 30^{o}C, reaching average maximum temperatures of 34^{o}C. In Hanoi in northern Vietnam, the lowest average temperature is 17^{o}C in January and February and average temperature in June until August is 29 ^{o}C with an average maximum at 33°C (Climate-Data.org 2019). The discrepancies in temperature, the amount of rainfall, and flooding season impact the agricultural practices in the various areas.

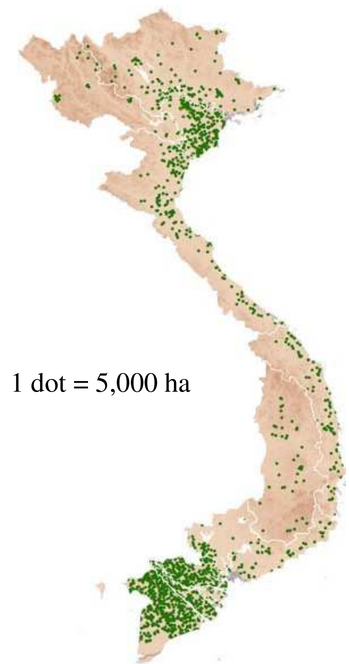


Fig. 1.2 Rice growing area in Vietnam (*IRRI 2015*)

Rice is the most important food crop in Vietnam. According to the report of FAO (April 2018), Vietnam produced 42.8 million tons of rice corresponding to 27.8 million tons on milled basis and exported 6.3 million tons milled rice in 2017. The main cropped area remained largely unvaried at 3.1 million hectares and the total cultivated area of three crops each year were approximately 7.7 million hectares (Ricepedia 2012). The average yearly yield per ha is 5.9 tons rough rice or 3.7 tons milled rice.

The Mekong and Red River deltas are two largest rice-granaries in Vietnam. About 18 million people lived in the Mekong Delta (Vietnam Government 2018), but 20.2 million in the Red River Delta (GSO 2012). The Mekong Delta area comprises 4 050 000 ha, the Red River Delta only 2 100 000 ha. In 2014, 52 % of the Vietnamese rice was produced in the Mekong area and 18% in the Red River area (IRRI 2015). One reason is that three crops per year can be harvested in the Mekong area: Winter-Spring (November –March), Summer-Autumn (May – September) and the Rainy Season (July – January) (Ricepedia 2012; Liew et al. 2014; Clauss et al. 2018; USDA Foreign Agricultural Service 2019). In 2018, winter rice was cultivated on 180 000 ha, spring rice on 1 595 000 ha, and autumn rice on 2 300 000 ha. In the Red River Delta only 573 900 ha are used for rice production (GSO 2012). There are only two main rice-cropping seasons in the Red River delta: a spring season and a summer season (Duy et al. 2015). Although the rice-growing area of the Mekong River delta comprises 30% of the gross national rice area, this delta contributes to 57% of the country's rice production (after data from USDA Foreign Agricultural Service 2019). More than 90% of Vietnam's rice exports come from the Mekong River Delta.

The Mekong River is a plentiful source of water for irrigation. The annual inundation also supplements large amounts of suspended sediment of about 160 million tons per year (Hung 2011). Water and sediments deliver nutrients for the paddy soils and rice plants, leading to higher rice productivity. On the other side, the Mekong delta is a low-level plain with many areas not more than 3 meters above sea level and criss-crossed by a complex system of channels and rivers (Ninh 2008). The delta may more and more affected by climate change related disasters such as increase of numbers and intensity of tropical storms, floods, inundation, and sea level rise that cause land loss, salt water intrusion as well as deterioration of soils and aquifers by salinization along the coast and the river channels (Ninh 2008). A similar situation exists for the low-level plain of the Red River Delta (Yen et al. 2017). Forecast models by FAO (2011) for the northern mountain regions in Vietnam indicated that rice production may drop under the influence of climate change by 12.5% in 2050 and 16.5% in 2070 due to floods, droughts, landslides, and fire.

In many zones, rice is grown in rotation with other crops especially in areas with restricted irrigation or in rain-fed areas. These cropping methods are differentially applied depending on climate (precipitation, temperature), soil parameters, season and individual and local nutrition preferences, market prices etc. In the Red River delta, maize and potato are planted alternately to rice. In the central region, a rice-subsidiary (mungbean, sesame, sweet potato, maize, groundnut, etc.) rotation system is widely practiced. In the Mekong Delta, rice-vegetable rotations are popular (FAO 2002).

1.2.2 Previous researches on harmful element concentration in Vietnamese soils and groundwater

Chu (2011) analyzed paddy soils adjacent to mine waste dumps. The results showed that Pb concentrations of 1271 - 3953 mg kg^{-1} in Tan Long, Thai Nguyen Province and 250 - 770 mg kg^{-1} in Chi Dao, Hung Yen Province in northern Vietnam, exceeding 3–56 times the Vietnamese allowable Pb level of 70 mg kg^{-1}. Phuong et al. (2010) identified Cu, Pb, and Zn enrichments in soils close to a copper-casting handicraft village in Hung Yen Province. The results analyzed paddy soils of Lam Thao, Phu Tho Province in the north irrigated with industrial wastewater (Vinh et al. 2012) indicated high concentrations of Cu (204 mg kg^{-1}), Zn (714 mg kg^{-1}), and Pb (140 mg kg^{-1}), surpassing the Vietnamese permissible limits of 50, 200, and 70 mg kg^{-1}, respectively. Huong et al. (2008) pronounced mean concentrations of Cd (4 mg kg^{-1}), Cu (202 mg kg^{-1}), Pb (159 mg kg^{-1}), and Zn (192 mg kg^{-1}) in waste water-irrigated paddies along To Lich and Kim Nguu Rivers close to Ha Noi, what is by far higher than their allowable soil limits.

Dissolved trace elements in water are the preferred forms for plant uptake. For example, the highly mobile As(III)-species which prevail in groundwater has a high bioavailability.

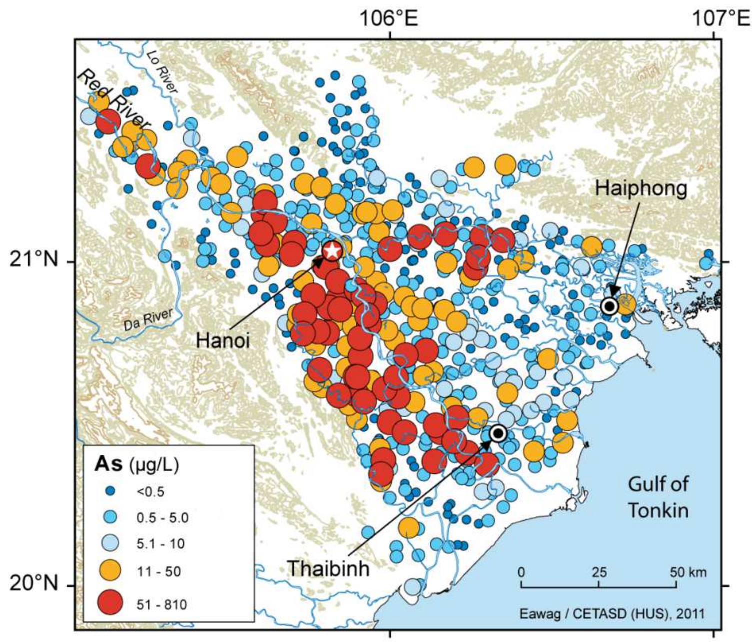


Fig. 1.3 Arsenic concentration in groundwater in Red River delta, Vietnam (*Winkel et al. 2011*)

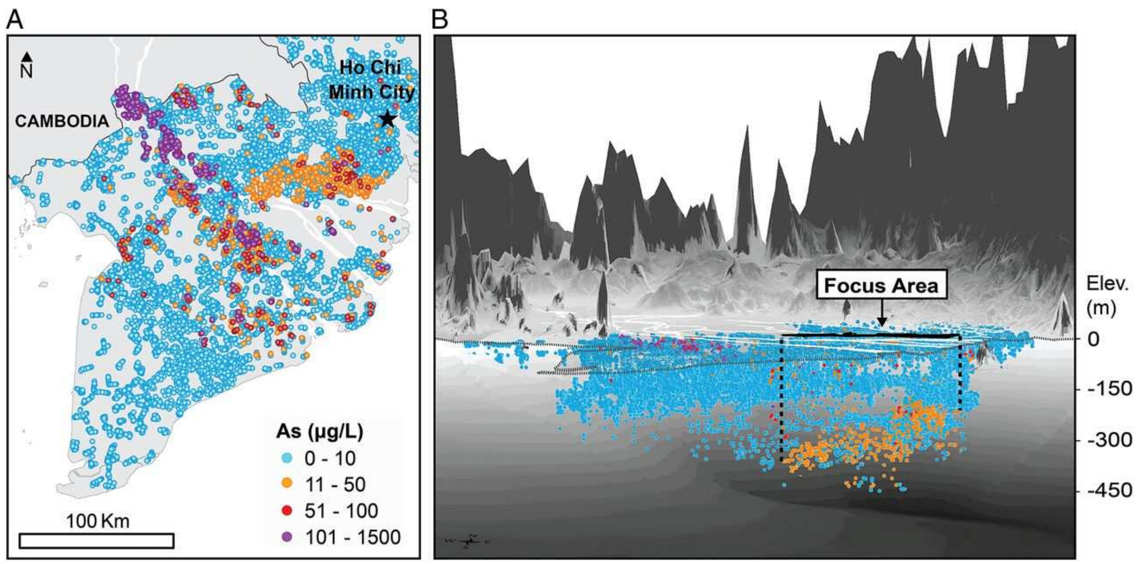


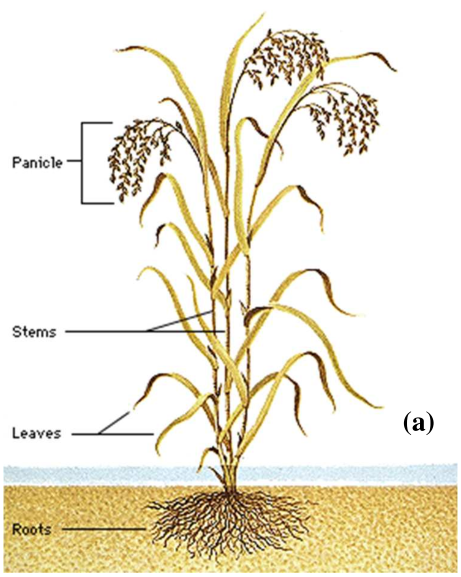
Fig. 1.4 Arsenic concentration in groundwater in Mekong River delta, Vietnam (*Erban et al. 2013*)

Therefore, studies on trace elements in the water are of interest for this work. Some publications showed that the exceedance of standard guidelines for arsenic concentration in drinking water given by WHO (10 µg L^{-1}) were found in 86 % of the studied groundwater samples in Red River delta (Jessen 2009; Sø et al. 2018; Viet et al. 2019). In Mekong River delta, 26 % of the groundwater samples contain higher As concentrations than drinking water guideline value of 10 µg L^{-1} ruled by USEPA, 74 % have the Mn concentration higher than the guideline of 0.05

mg L^{-1}, and 50 % surpass the guideline of 0.3 mg L^{-1} for Fe (Hoang et al. 2010). Similarly, 27%, 91%, and 27% of the shallow well-water samples in Tien Giang and Dong Thap provinces in the Mekong River delta exceed the WHO guidelines for As, Mn, and Ba respectively (Shinkai et al. 2007). High As concentration in Mekong delta groundwater are also recognized by Stanger et al. (2005), Erban et al. (2013), and Merola et al. (2015). In general, the distributions of high arsenic groundwater in two areas Red River and Mekong River deltas are not uniform and also depend on the sampling depth in the aquifer as shown in Fig. 1.3 and 1.4 respectively.

1.3. Physiology and varieties rice plants (Oryza sativa)

Rice (Oryza sativa) is a graminoid species of plant in the family true grasses (EOL 2004). Rice can be grown in the wide range of terrains from mountainous lands to low land delta areas under tropical, subtropical and moderate climate (Vijay and Roy 2013).



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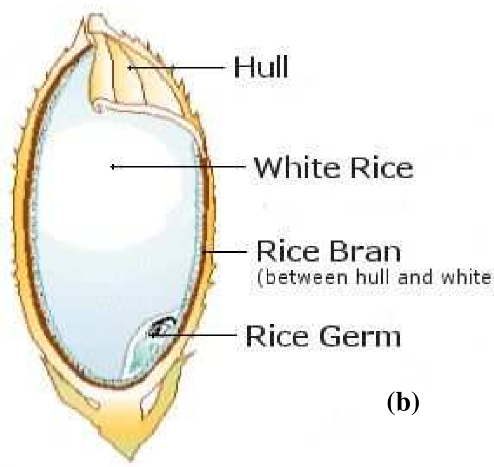

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Fig. 1.5 (a) Rice plant and (b) whole rice grain

In Vietnam, rice is harvested by cutting the whole aboveground rice plant (from 5 - 10 cm above the soil surface). Roots and stubbles are always left in the fields. The whole aboveground rice plant includes stems, leaves, and panicle as seen in Fig 1.5a. Whole rice grains are normally separated from the plant by using a threshing machine. After harvesting, stubbles and straw are sometimes burnt in situ, what prevents the accumulation of organic matter in the paddy fields. The whole rice grain (Fig. 1.5b) comprises the husk (or hull) and unpolished rice grain. These two compounds are then separated by a rice hulling machine. The structure of unpolished rice is composed of starchy endosperm, bran, and germ as illustrated in Fig 1.5b.

Shoot and husk of rice may now be applied for the various purposes. For a long time, shoot is utilized as animal bedding, cooking fuel, reclaiming soil, or organic fertilizers. In some areas, shoot is directly burnt in situ. Nowadays, husk is applied in many fields: producing heat/electric power (electricity), generating activated carbon, use as fertilizer and substrate, separating crystalline silica for brick and ceramic production (Kumar et al. 2013). Furthermore, husk ash is also exerted as an absorbent with a large surface area (Bazargan et al. 2014; Prasara and Gheewala 2017).

According to the FAO's data (FAO 2002), there are 24 rice cultivars that have been planted in the north and north central regions of Vietnam, 44 cultivars in southern and south-central regions, 12 cultivars in irrigated and rainfed lowland regions, and 7 cultivars in upland areas. The rice cultivars are typically chosen according to the climate condition, the availability of water, and soil conditions in a certain area.

1.4 Nutrient and harmful element concentrations in rice

Rice is the food major staple of nearly 40% of the world population. 90% of the rice are cultivated and consumed in Asia (Vijay and Roy 2013). Rice is a main food in Vietnam as well as in southern and eastern Asia. Rice and rice-based products are present in breakfast, lunch, and dinner meals of Vietnamese adults. They cover almost all daily needs on carbohydrates – providing energy. Vietnamese eating habits can be dissimilar among areas having a great natural diversity of dishes and ingredients. In 2018, the yearly amount of milled rice consumed per capita in Vietnam was average 153 kg, only behind the residents of Bangladesh (180 kg), Myanmar (194 kg) and possibly Cambodia (159 kg) (FAO 2019). For comparison, European Union people consumed averagely 5.7 kg rice per year.

The main rice compounds are starchy carbohydrates, accounting for up to 90% of the total dry weight and 87% of the total caloric content (Arnarson 2017). Rice just supplies a very small amount of proteins (2.4%) and virtually no fat. In addition, rice also contains other essential compounds such as thiamine, riboflavin, niacin, vitamin E, zinc, potassium, iron, and fiber (Schenker 2012).

A link between high carbohydrate intakes and a risk of chronic diseases like obesity, diabetes II, metabolic syndrome, and cardiovascular disease is assumed (Schenker 2012).

Other hazardous health effects that Asian communities are facing are a chronic intake of toxic elements by rice consumption. Rice is considered to be a major intake sources for As and Cd (Tsukahara et al. 2003; Arunakumara et al. 2013; Chaney et al. 2016; Shraim 2017) for people consuming daily a large amount of rice. Furthermore, other potentially harmful elements like Pb, Cr, and Mn may also be enriched in rice grains in some areas (Norton et al. 2014; Shraim 2017).

Some authors investigated the As intake from rice consumption. Sigrist et al. (2016) analyzed high total As (tAs) concentrations in rice (0.09 - 0.32 mg kg^{-1}) and rice products (0.05 - 0.20 mg kg^{-1}) in Argentina. Wheat products accounted for 53% and rice products for 17% of the inorganic As (iAs) intake. The tAs concentrations in some studied rice grains in Italy fluctuated from 0.11 to 0.28 mg kg^{-1} (Sommella et al. 2013), corresponding to only 1.1 % - 2.8 % of the tolerable upper intake As level (2.1 µg kg^{-1} b.w.) if rice consumption is 5.38 kg $year^{-1}$ and average Italian body weight (b.w.) of 70 kg (after data from Walpole et al. 2012). Similar low risks of As intake by rice were also estimated for France where the daily tAs intake varies between 0.002 and 0.184 µg kg^{-1} b.w. by rice corresponding to 0.1% - 8.8% of the permissible As level (Jitaru et al. 2016). In Pakistan, wheat and rice contributed 5 % and 1 % of the total daily intake of iAs perspectively while 74% was from water (Rasheed et al. 2018). In some contaminated areas in Korea, local habitants ingested by eating rice 50% of the tAs threshold (2.1 µg kg^{-1} b.w.) and and 80% of the Cd threshold (0.36 µg kg^{-1} b.w.) (Kwon et al. 2017). For Hong Kong people, rice consumption leads to 10% - 18% iAs of the permissible As limit (Wong et al. 2013). Notably, Chinese people ingest 71% - 171% of the permissible maximum As level from rice consumption (Lei et al. 2013; Liao et al. 2018). A study in the major arsenic-contaminated area in Nadia district, West Bengal (India) revealed that the mean tAs concentration was the highest in rice (0.451 mg kg^{-1}) in comparison with wheat, common vegetables, and pulses (Bhattacharya et al. 2010). It exceeds the permissible maximum concentration of 0.37 mg tAs kg^{-1} in rice (if assuming that the iAs concentration contains 54% of the tAs concentration in rice according to Suriyagoda et al. 2018. Similarly, Arunakumara et al. (2013) reported the extremely high total As concentrations in rice grains collected in Nadia district, West Bengal, India (0.25 - 0.72 mg kg^{-1}). These authors cited data from other countries, revealing also high As concentrations in rice from the Xingyi region in Southwest China and some regions in Bangladesh.

Xie et al. (2017) found that 15.5% and 4.6% of the 110 leading Chinese rice cultivars had Cd and Pb concentrations exceeding the allowable maximum concentration of 0.2 mg kg-

^{1} for each element in rice. An earlier study by Fang et al. (2014) also indicated that Pb and Cd concentrations in rice from the main rice growing areas in China surpassed their allowable concentrations in 4.3% and 3.3% of 92 samples respectively. In Japan, two heavily Cd-contaminated zones are the Jinzu River basin and Kakehashi River basin, where the Itai-Itai disease was detected in 1968. The Cd concentrations in rice range from 0.02 – 1.06 mg kg^{-1} and 0.11 - 0.67 mg kg^{-1} respectively (Nogawa et al. 2004). Uraguchi and Fujiwara (2012) reported that the average Cd intake of Japanese people was 0.43 µg kg^{-1} b.w. day^{-1}, higher than the tolerable upper Cd intake level of 0.36 µg kg^{-1} b.w. day^{-1}. According to Satpathy et al. (2014), rice samples from the East Coast of India contain 0.01 - 1 mg kg^{-1} Pb and 0.1 - 0.6 mg kg^{-1} Cr exceeding partially their permissible concentrations of 0.2 mg kg^{-1} for each element.

Despite being one of world' leading rice producing and consuming country, Vietnam shows still a strong deficiency of a systematic comprehensive research on the element uptake of rice plants from the soil and a lack of appraisals of human's health risks from rice eating. There are a few studies at some locally contaminated regions. The concentrations of As, Cd, and Pb in studied rice in Lam Thao, Phu Tho Province exceeded 2 - 4 times the allowable concentration of 0.2 mg kg^{-1} for each element (Vinh et al. 2012). Rice grown close to To Lich and Kim Nguu Rivers in Ha Noi Province reached Pb concentration of 2.1 mg kg^{-1}, 10-time higher than its allowable concentration (Huong et al. 2008). The elevated As and Pb concentrations in rice are assumed to primarily caused by geogenic sources (Ma et al. 2017).

Different to the much less toxic organic As compounds such as arsenobetaine and arsenosugars which are most prevalent forms in fish and seafood, the overwhelming inorganic arsenic and single methylated arsenic species (monomethylarsonic acid - MMA and dimethylarsinic acid - DMA) in terrestrial foods can lead to serious health problems (EFSA 2015; Cubadda et al. 2017). Therefore, most of current risk assessments of daily arsenic exposure are based on the inorganic forms. In rice, the ratios of inorganic As change considerably depending on its speciation in soils and on the variety of rice. An evaluation of different species studies in different countries by Suriyagoda et al. (2018) showed that iAs concentration comprises 54% of tAs concentration in rice grain (data were compiled from different countries and market data). Alternatively, this percentage in China rice is 67% (Lei et al. 2013) while in S and SE Asian rice is 80 - 91% (Rahman and Hasegawa 2011). Some researchers identified As^{III}-species as the dominant compound in rice (Seyfferth et al. 2011; Patel et al. 2016; Ma et al. 2017).

1.5 Health risk of potentially harmful elements

Arsenic

Arsenic is a naturally occurring metalloid and ubiquitously found in the environment (groundwater, food, soil, and air) in both inorganic and organic forms (Singh et al. 2011). In the environment, its universal oxidation states are trivalent arsenite (As^{III}) and pentavalent arsenate (As^{V}) forms. Arsenic in groundwater and soil primarily exists as inorganic oxy-anions (AsO_2^-, AsO_4^{3-}, $HAsO_4^{2-}$, $H_2AsO_4^-$, etc.). Arsenic is considered as a hazardous element positioned first in the list of toxicants which elicit the seriously potential threat to human health. It is called the "king of poisons" and causes serious health threats on a worldwide scale (Hughes et al. 2011; Singh et al. 2011; Tyler and Allan 2014). According to EFSA (2014a), the International Agency for Research on Cancer (IARC) classified As and inorganic arsenic (iAs) compounds as Group 1 carcinogen to human. An estimated 100 million people worldwide is confronted with As concentrations in drinking water surpassing the WHO provisional guideline of 10 µg As L^{-1}, an estimated 45 million people are exposed to more than 50 µg As L^{-1} (Shankar et al. 2014; Tyler and Allan 2014). As mentioned by Shankar et al. (2014) about 150 million people around the world are estimated to be affected with an increasing prospect as new affected areas are continuously discovered.

The toxicity of arsenic depends on its species. Inorganic arsenic forms are generally more widespread and are assumed to be more toxic than organic forms, although in some cases monomethylarsonous acid (MMA^{III}) may be more toxic than inorganic As^{III}, the species with the highest toxicity (Shankar et al. 2014). Excessive and prolonged exposure to As may result in arsenicosis to skin, brain, and internal organs. Arsenic poisoning causes skin disorders; cancers of bladder, kidney, and lung; diseases of the blood vessels of the legs and feet, diabetes mellitus, increased blood pressure, cardiovascular abnormalities, and reproductive disorders (EFSA 2009a; Singh et al. 2011; Shankar et al. 2014). Besides, arsenic impairs neurological functions leading to memory deficit and mood disorder even at low As concentration, particularly in children (Tyler et al. 2014).

Cadmium

Similar to arsenic, cadmium is classified as Group 1 – human carcinogen by the IARC. Acute Cd exposures can lead to severe health problems like cancer of the lung, prostate, kidney, endometrium, bladder, or breast (Bertin and Averbeck 2006; EFSA 2009b). In addition, Cd may also damage internal organs resulting in renal dysfunction, bone demineralization and disorder, immuno-suppression, and eventually to renal failure (Bertin and Averbeck 2006; EFSA 2009b). On cellular level, Cd may cause cell proliferation, differentiation and finally apoptosis (Bertin and Averbeck 2006). For the non-smoking population, foodstuffs are the major contributor of Cd exposure. Compared to inhalation exposure, Cd is relatively low absorbed through dietary pathways and contributes only to 3 - 5 % of the total oral and inhalational Cd intake. Yet, it is efficiently and persistently stored in kidney with a biological half-life from 10 to 30 years (EFSA 2009b). Cadmium exist in the environment mainly as inorganic species although it may be bound to proteins and organic compounds.

Lead

Lead is enriched in the environment by anthropogenic activities. It is broadly used in industrial activities, as lead shot, formerly in gasoline and house paint, plumbing pipes, pewter pitchers, storage batteries, toys and taps (EFSA 2012; Jaishankar et al. 2014). In the past, it was emitted into the air and water bodies together with other heavy metals by smelting non-ferrous metal ores beginning already before the Middle Ages (Deicke et al. 2006), later additionally by coal burning. Beside air, drinking water, industrial processes, and domestic sources, food can be a main factor contributing to Pb exposure (EFSA 2012), resulting in varying exposure to people. Inorganic Pb forms is predominantly accumulated in bone with a half-life of 10 – 30 years, and may slightly enriched in blood with a half-life of about 30 days (EFSA 2012). Pb can provoke hematological, gastrointestinal, and neurological dysfunctions (Stohs and Bagchi 1995; EFSA 2012).

Manganese

Manganese is as a component of a number of metalloenzymes an essential dietary element (EFSA 2013). Deficiencies may cause adverse effects of health. Thus, EFSA's report just focused on Adequate Intake for different age groups, but the toxicity of an increased Mn exposure is less considered. Increased Mn intake via inhalation, drinking water, and food may lead to neurotoxic reactions of adult and particularly children and may decline child intellectual functions (Wasserman et al. 2006).

Some other harmful elements

Chromium and nickel can be enriched in food and drinking water. Both elements are classified as human carcinogens by the IARC (EFSA 2014b; Casalegno et al. 2015; EFSA 2015; Nordberg 2015).

Nickel and its compounds may increase the risk of cancer of the lung, the nasal cavity, and paranasal sinuses by inhalation exposures. However, no tumors have been found in oral pathway studies. Thus, the CONTAM Panel assumed that dietary Ni intake is unlikely to provoke cancers (EFSA 2015). However, acute Ni oral-exposure is responsible for non-carcinogenic health risks in the gastrointestinal, haematological, neurological and immune system.

Chromium toxicity depends on its oxidation state and speciation. Cr^{III} compounds are less toxic than Cr^{VI} compounds in general. Cr^{III} organic compounds show unobvious adverse effects during oral exposure whilst Cr^{VI} compounds increase the risk of intestinal tumors (EFSA 2014b; Casalegno et al. 2015).

1.6 Measures to lower the uptake of toxic element by rice

The uptake level of toxic metals and metalloids may influence the growth and yields of rice plants (Fahad et al. 2019; Pandey and Dubey 2019). More importantly, their uptake may cause adverse impacts for the human health. Researches about the mechanism of element uptake into rice plant and translocation within plant tissues were published with a main focus on the very relevant toxic elements As and Cd. Such investigations may help to find solutions in order to alleviate the uptake of these harmful elements, but may also deliver a more comprehensive explanation for the element transfer from soil into the rice plant as presented in this dissertation.

Suriyagoda et al. (2018) stated that the translocation of As from soil into rice plant was strongly dependent on the As quantity and speciation in the rhizosphere. In anaerobic soils, arsenate $[As^{V}O_4]^{3-}$ is reduced to arsenite $[As^{III}O_3]^{3-}$ which is less sorbed by root Fe-plaques. The enrichment of the highly mobile arsenite in the soil solution facilitates its transfer into the plant. Arsenite is taken up by a subclass of aquaporins (water channels consisting of integral membrane proteins), and then enters the stele following mainly the Si-uptake pathway. In aerobic soils, the As^{V}-species presents the main bioavailable form. Due to the structural analogy between arsenate (AsO_4^{3-}) and phosphate (PO_4^{3-}), this species shows strong similarities to the phosphate uptake. The typical organic As species, MMA and DMA, are transported at a much lower rate than inorganic forms into the plant. Some efficient methods are proposed to limit the As uptake. Panthri and Gupta (2019), Suriyagoda et al. (2018), and Shakoor et al. (2019) proposed some strategies to reduce the accumulation of As in rice as follows:

- Rice cultivation should be under changing anaerobic/aerobic, intermittent flooding or alternate wetting and drying (AWD) soil conditions, rather than permanently in submerged soils. The efficiency of AWD for decreasing the As uptake was reported earlier by Hu et al. (2013), Yang et al. (2017), and Carrijo et al. (2018).

- Application of biochar, sulfur, or remnants from rice polishing to soil;
- Use of adequate doses of P, Fe, and Si;
- Use of irrigation water with low As concentration;
- Use of rice genotypes with low As uptake by the grains;
- Use of cooking water with low As concentrations.

Many authors (cited by Li et al. 2019) reported that the addition of reactive Si into the paddy soils reduces the As uptake by rice. However, Li et al. (2019) experienced that in an As-contaminated soil the As concentration in shoot and root of the rice cultivar Nanjing 44 increased with the reactive Si (sodium silicate) concentration, whereas the rice cultivar Zhendao 10 was not significantly affected. They refer that the kind of added reactive Si the type of cultivar, but also the formation of Fe-plaque at the root of rice have a strong influence on the As-uptake. Wu et al. (2016) investigated the As uptake and speciation in indica and hybrid rice genotypes with different radial oxygen losses (ROL) in the root area, whereby the indica genotypes with higher ROL accumulated less inorganic As in grains. Reason is the more pronounced formation of Fe-rich plaque in the high ROL genotypes, what may be additionally enforced by reactive Si addition.

Rice primarily takes up Cd as Cd^{2+}-species. The uptake ability is dependent on cultivar and growth conditions (Rizwan et al. 2016). Wang et al. (2015) evaluated that Cd^{2+} and Ca^{2+} have a similar uptake route. Some of the aforementioned As strategies may also hamper the Cd-uptake: AWD (Hu et al. 2013), application of nutrients, lime, reactive silica, compost, and biochar lower the Cd uptake (Rizwan et al. 2016; Babu and Nagabovanalli 2017; Kosolsaksakul et al. 2018; Yang et al. 2018).

In general, the extend of Fe-rich plaque formation, higher concentrations of reactive Si, and AWD conditions may decrease the transfer of As (Panthri and Gupta 2018; Suriyagoda et al. 2018; Seyfferth et al. 2018), Cd (Cheng et al. 2014; Rizwan et al. 2016), and Pb (Liu et al. 2011; Cheng et al., 2014; Lai et al. 2018). Lai et al. (2018) refer additionally to the strong role of Pb sequestration by iron oxides in rhizosphere soils rather than by the plaques at the root surfaces.

Another parameter important for a safer rice production is the pH-value. Kim et al. (2016) demonstrated that a pH-change induced by immobilizing agents such as dolomite, steel slag, and agricultural lime is a feasible approach to lower the Cd and Pb uptake in contaminated paddy soils.

In future studies, the interaction of the combined interacting parameters must be investigated in much more details to get a better basis for improving practical cultivation and management measures in order to mitigate the accumulation of potentially toxic elements in rice. These parameters are: AWD, role of soil conditioners, redox conditions, pH-value, pore water geochemistry, the concentration of reactive Si and phosphate, influence of cultivars, ROL, formation and composition of plaque, Fe and organic matter phases in the rhizosphere soil etc. This kind of research should be complemented by systematic physiological, microbiological, biochemical, and species investigations, elucidating the mechanisms behind the transfer of toxic elements from the soil to the rice plant and within the plant - as shown by Kumarathilaka et al. (2018), Wang et al. (2019) and Panthri and Gupta (2019) for As, and by Fahad et al. (2019), Pandey and Dubey (2019), and Roychowdhury et al. (2019) for additional critical elements. Further research is needed to understand the interactions between different elements, the role of pore water chemistry, microbial processes, and speciation of the elements, as well as the plant uptake and accumulation mechanisms especially in rice grains. The new knowledge may help to mitigate the impact of harmful elements on the population, but also to understand much better their transfer mechanisms in the soil-water-plant system.

For area with high toxic elements concentrations in rice grains, it should be surveyed if other crops with a lower uptake of critical elements should be alternatively cultivated. In addition, to restrict exposure to harmful elements, local people should consume polished rice instead of unpolished rice. Some studies indicated that although the bran layer in unpolished rice is a storage to supply nutrients like K, Zn, and Ca (Seyfferth et al. 2011), but it also leads to higher risks of As and Cd. Eating polished rice could decrease level of inorganic As by 10% (Meharg et al. 2008; Naito et al. 2015) and of Cd by 3% (Moriyama et al. 2003).

1.7 Structure of the thesis

Chapter 1 represents the background and framework of this thesis. An overall view of research area including facts on weather and climate, population, water sources, and on rice harvesting in three studied areas are described. Some previous investigations on trace element concentrations in paddy soils and rice are summarized. Structure, variety and composition of rice plants are summarized. In addition, potential health risks and possible adverse effects through rice consumption are assessed.

In Chapter 2, all materials and methods used in this work are described in detail. Collecting and the preprocessing of samples in Vietnam, the pretreatment and digestion processes of samples in the geosciences laboratories are carefully described. The applied analytical techniques ICP-MS and ICP-OES for the quantification of main, minor, trace and ultratrace elements are presented together with an evaluation of the precision and accuracy of measurements.

Chapter 3 comprises the soil geochemistry and the element transfer into rice grain in the Red River delta in the north and Huong River in the center of Vietnam. Because of lacking geochemical data for the parent materials, the soil data are compared with average values of the upper Earth crust and average global shale to find out if the soil samples are contaminated or enriched. Groups of elements with high positive correlation coefficients are classified. The element concentration data are additionally used to get more information about the soil characteristics, especially concerning the role of oxide/hydroxides of Fe, Al and Mn, but also to get an approximate indication for the presence of clay minerals. These phases together with the pH-value and the organic matter in the soil help to understand the fixation or release mechanisms of potentially toxic elements and their contributions to the element bioavailability. The concentrations of potentially harmful elements in unpolished rice grains are used to calculate the amounts of single elements taken up by eating rice. The potential health risk for the local population can be deduced by comparing these amounts with the tolerable upper intake level or the permissible maximum concentration in rice grains.

In Chapter 4 paddy soil geochemistry and the transfer of elements into rice grain in Mekong River delta in the south are described and interpreted similar to the preceding chapter and again a health risk assessment has been performed. In addition, regression models on basis of the SPSS statistical analysis are calculated for single harmful elements in soil to predict their concentration on main soil factors such as reactive phases and pH-values. Depending on the main soil compositions, concentrations of trace elements can be computed with low errors by multivariable statistical analysis for uncontaminated soils. A comparison for all three investigated areas is performed.

In Chapter 5 the selective transfer of elements from soil into single parts of rice plant (whole aboveground plant, shoot, husk, and unpolished rice) is evaluated. It elucidates the different translocation and uptake patterns within the plant again in dependency of soil factors. In addition to chapter 3 and 4, chronic non-carcinogen and carcinogenic health risk assessments for the three areas are performed by rice consumption.

Chapter 6 summarizes the most important results of this study and shows perspectives for the future research.

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Chapter 2

Material and Methods

2.1 Sample collection and processing

Rice and corresponding paddy soil samples were collected at 110 sites along three river systems: Mekong River in the south, Huong River in the center, and Red River in the north of Vietnam. At each sampling location, one representative complete rice plant was extracted along a path inside the rice field. The soil was taken directly from the extracted root within 0 - 10 cm depth. The corresponding rice plant samples were cut at approximately 5 - 10 cm above the soil called aboveground rice. Aboveground rice and soil samples at 30 positions were gathered in September 2015 in the Red River and Huong River areas. 80 sites were collected in April 2017 in the Mekong River delta. The sample collection took place within 10 days before the typical rice harvesting time. Maps of the sample locations are shown in Fig. 2.1

After collecting, all soil samples were air-dried at the room temperature for 2 - 3 days. Plant roots and gravels were removed from soil by hand. The soils were then sieved to particle sizes <2mm. The plant samples were dried in sunlight at 40 - 50^{o}C for 2 days. Then, all of the samples were transported to the laboratory of the Geoscience Center of Georg-August-University.

At the laboratory of the Geoscience Center, the soil samples were dried again at 105^{o}C and the rice samples at 60^{o}C. The soil samples were pulverized into particle sizes <63 µm by an agate ball mill (Fritsch, Pulverisette 5). The 24 rice plants from north and central Vietnam were separated into shoot (stems and leaves), husk, and unpolished rice. The 78 whole rice grains from the Mekong area were split into husk and unpolished rice. The shoot and husk samples were pounded into particle sizes <63 µm by an agate ball mill (Fritsch, Pulverisette 19). The unpolished rice samples were milled by using an agate mortar.

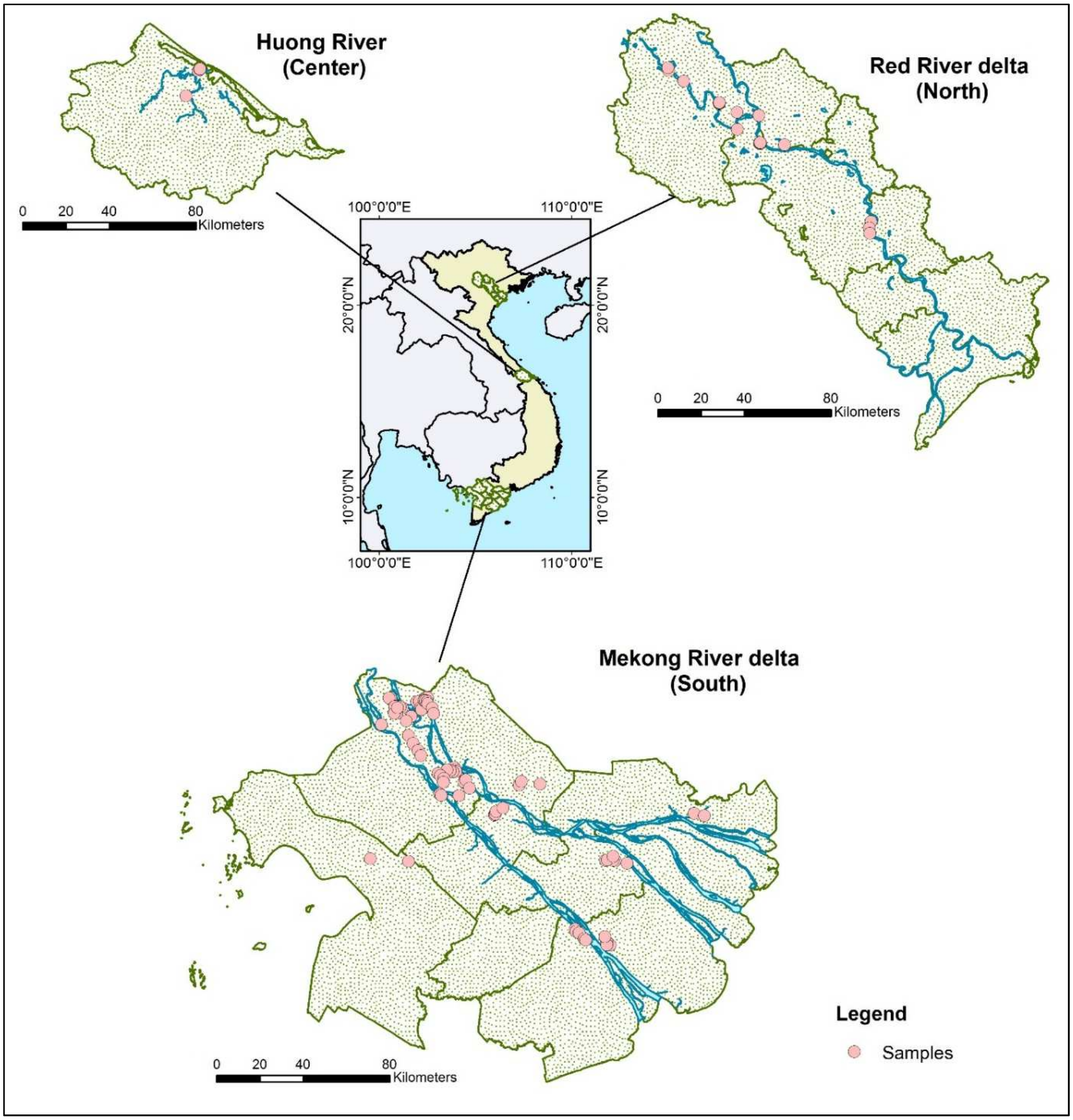

Fig. 2.1 Sample locations in the three investigated river areas in Vietnam

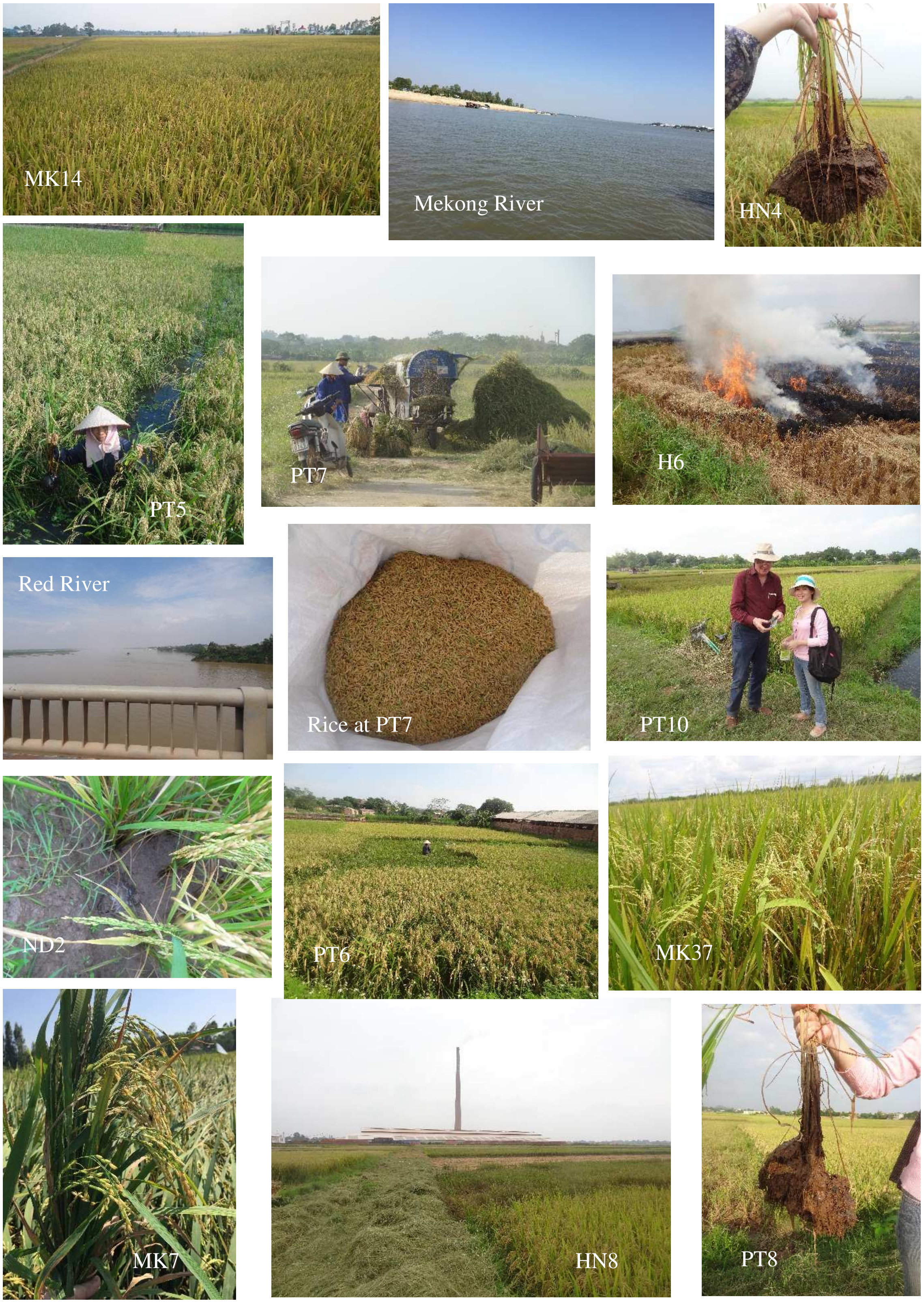

Fig. 2.2 Photos of some research sites

2.2 Determination of pH-value and LOI (loss on ignition) in soil samples

Soil pH-value

A mixture of 10 g air-dried soil (particle sizes <2mm) and 25 ml 0.01 M $CaCl_2$ solution was stirred for 10 minutes and then kept quiet for one hour. Then, the pH-value in the liquid was measured by a glass electrode connected to the WTW ProfiLine pH/mV-Meter 197. The measurement was repeated in triplicate to get the mean soil-pH value.

Loss on ignition (LOI)

The LOI represents a proxy for the content of organic matter (OM) and of water in clay mineral and oxides/hydroxides. It was determined as follows: About 500 mg of 105 ^{o}C dried, powdered soil (particle sizes <63 µm) were placed into a small ceramic crucible and heated up to a temperature of 530^{o}C for 2 hours. After that, the ceramic crucibles were cooled down in the desiccator to room temperature. The weight loss divided by the initial weight and multiplied by 100 to get the LOI content in percent.

2.3 Element analysis of soil and plant material

The digestion processes of soil and plant samples were executed according to the procedure stablished at the laboratory of the Geoscience Center: Approximately 150 mg of soil or 700 mg of plant powder (particle sizes <63 µm) were completely digested by a mixture of ultra-pure concentrated HNO_3, $HClO_4$ and HF in a closed ultra-clean PTFE vessel (PicoTrace®, Bovenden, Acid Sample Digestion System DAS 30). The digestion procedure consisted of 5 steps: 1. pre-reaction of the samples with the acid mixture for 5 hours increasing temperature up to 100^{o}C in the loosely covered vessel; 2. pressure digestion in the closed vessels for 10 hours at 150^{o}C; 3. evaporation of the acids nearly to dryness by using an evaporation plate at 180^{o}C, CO_2 and SiF_4 are also removed; 4. after cooling down, addition of 2 mL concentrated HNO_3 and 0.5 mL HCl and 10 ml ultrapure water and heating for 2 hours at 150^{o}C to completely dissolve the evaporation residue; 5. transfer of the clear solution into a volumetric flask (100 ml for soil and 50 ml for plant) and storage in precleaned PE-bottles. Each digestion series comprised 32 positions. Each series included two digestion blank samples (only the acids without sample material) and at least one international reference standard material in order to determine an eventual contamination (from handling and acids) during the digestion and to get information on precision, accuracy and international comparability of the measurements. The clear solutions were then quantified by Inductively Coupled Plasma - Optical Emission

Spectrometry (ICP-OES, Agilent 5100 VDV) and - Mass Spectrometry (ICP-MS, Thermo Scientific iCAP Q), which were calibrated by a series of multi-element solutions containing the investigated elements in the expected concentration range of the unknown samples.

The detection limits for the single elements were calculated as 3-fold standard deviation of their concentrations in the blank samples from each set. The international reference samples comprised the following materials: lake sediment GSJ-JLk-1; bush branches and leaves NCS DC 73349; maize plant WEPAL-IPE-126; and the inhouse reference samples Wissenbach shale TW45. The finally selected element lines (ICP-OES) and masses (ICP-MS) were chosen based on the criteria (1) lowest detection limits and (2) best agreement with reference samples (see the listing in Table A1.1 in Appendix A1). In general, the accuracies of measurements for main elements were mostly better than 5% while those for trace elements fluctuated from 5% to 10%, except for Zr which with results were 20% lower than the certified values (reason: incomplete dissolution of the mineral zircon).

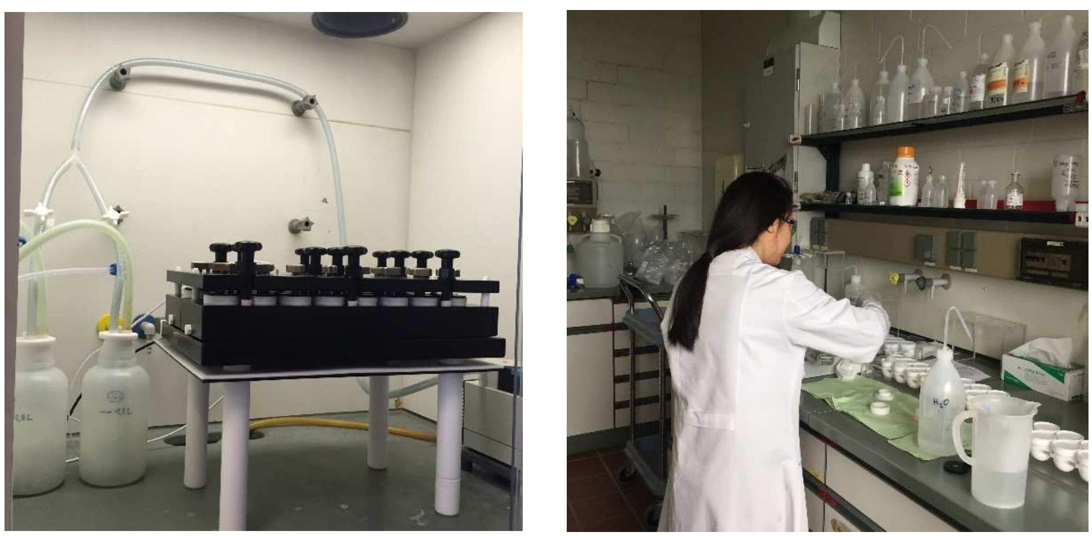

Fig. 2.3 Acid Sample Digestion System DAS 30 from PicoTrace® and dilution process

2.4 Calculation of physiological concentration and transfer factors of elements

Physiological concentration in rice plants

Washing plant samples before analysis is sometimes applied with the aim to remove adhering soil materials and air dust. This washing, however, may not completely eliminate the adhering particles and may partially remove elements contained in the plant tissue. In this study, the plant samples were directly analyzed without a washing step and then mathematically corrected for adhering material. This is the basis to calculate the physiological element concentrations in the plant. The physiological concentration represents the concentration of an element that enters the plant through the root (and to a very small extend through the aboveground plant parts like leaves or stalk). The calculation to correct for adhering particles in this work is based on three assumptions: (1) Adhering material can be represented by the local soil particles (this is a acceptable compromise even though a major portion of atmospheric dust consists of soil particle; unfortunately, a detailed sampling and analysis of the local atmospheric dust was not possible during this work); (2) There is only a negligible uptake of elements from the air; (3) Titanium can be used as an indicator element for adhering dust (Ti is considered not to be taken up by rice plants). Correction procedures for adhering dust and their limits are presented in detail by Pospiech et al. (2017). The calculation formulas for the physiological concentrations are presented in the section "Materials and methods" of Chapter 5. This calculation is only applied for plant, shoot, and husk concentrations. For the rice grain samples, a particle correction was not necessary, because of their generally very low Ti-concentrations (mostly below detection limit). The husks surrounding the grains prevent that atmospheric or soil particles advance to the grains.

Transfer factors (TFs)

Transfer factors (TFs) from soils to plant parts are calculated as the ratio of concentration of an element in plant/shoot/husk/unpolished-rice to its concentration in the corresponding soil as seen in "Material and methods" of Chapter 3. The transfer factor represents the ability of an element in the soil to enter the plant. To calculate this translocation ability, physiological concentration in the plant tissues must be applied.

2.5 Data and statistical analysis

This research applied the software IBM SPSS statistics 20 (1) to evaluate the influence of the main soil factors such as the concentrations of Fe, Mn, and Al (proxies for oxide/hydroxide and clay minerals) on the concentration of potentially harmful elements in soils, (2) to predict trace element concentrations in soils from soil factors. The procedure is described in section "Material and methods" of Chapter 4.

2.6 Health risk assessment

Health risk assessments of element exposure by rice consumption applied in this thesis include: (1) a comparison of the daily intake amount of an element by eating rice for a typical Vietnamese with the daily Tolerable Upper Intake Level; (2) a comparison between element concentration in rice grain with the permissible Maximum Concentration; (3) calculation of the chronic non-carcinogenic risks from selected harmful elements; and (4) calculation of chronic carcinogenic risks.

(1) Tolerable Upper Intake Level (UL)

Tolerable upper intake level (UL) is the permissible maximum level of total chronic daily intake of an element from all sources including food, supplements and drinking water. This threshold is judged to be unlikely to pose a risk of adverse health effects to humans and are regulated by the European Food Safety Authority (EFSA) and World Health Organization/ Food and Agriculture Organization of the United Nations (WHO/FAO). The ULs may be established for various life age groups. The ULs are not only applied to harmful elements but also to nutrients. An UL exceedance may cause an enhanced risk of adverse reactions. There are still insufficient UL data for some critical elements. In this work, the ULs (mg day^{-1}) have been calculated for Vietnamese adults with average body weight of 45 kg for a female and 58 kg for a male.

In addition, the intake of nutrients is compared with Daily Recommended Dietary Allowances (RDA). The RDA is the average intake level to respond the daily nutrient requirements of the human body (NIH 2015).

(2) Permissible Maximum Concentration in rice grain (MC)

Permissible maximum concentrations (MC) of some potentially harmful elements in rice products are regulated by European Union (2006). The MCs of inorganic As (iAs), Cd, and Pb in rice grains are 0.2 mg kg^{-1} for each element. These regulations have been applicable for the European Union whose population consumed 2017 a very low amount of rice of on average of 15.6 g per day and capita (FAO 2019), 27 times less than Vietnamese people.

(3) Non-carcinogenic risk assessment

Chronic harmful element exposure causes non-carcinogenic adverse effects for human health. The Chronic Hazard Index (HI) helps to estimate the total non-cancer risks of harmful elements for human lifetime exposure. The HI integrates the exposure level and the related toxicity into just a value (USEPA 1989; Nordberg 2015). The HI is calculated by the sum of individual non-cancer risk of an element called Target Hazard Quotient (THQ). The calculation for these indexes are indicated in Materials and methods section in Chapter 5.

The HI approach is suitable to compare the toxicity level of foodstuffs or mixtures with each other. Nordberg (2015) noted that this index should be interpreted carefully. It can be used to compare the hazard risk levels among foodstuffs/mixtures. For example, it is feasible to collate the health risk level between rice and wheat to a local community.

(4) Carcinogenic risk assessment

The chronic cancer risks over a lifetime can be judged for individual carcinogenic factor by index Incremental Lifetime Cancer Risk (ILCR) and for total carcinogenic factors by the index Cumulative Cancer Risk (∑ILCR) (USEPA 1989). The healthy safe level proposed by USEPA (1989) should be below 10^{-6} and the acceptable level is in the range of 10^{-6} to 10^{-4}.

In this approach, two most important carcinogens As and Pb are adjusted for rice. Although Cd is a ubiquitous dangerous carcinogen, its carcinogenic risk comes primarily from inhalation exposure rather than from dietary exposure, so slope factor parameter of oral Cd exposure cannot be used here. Similar to non-carcinogenic risk index HI, the incremental carcinogenic risk index ∑ILCR is appropriate to compare foodstuffs/mixtures with each other. The formulas for these indices are exhibited in the Materials and methods section of Chapter 5.

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Chapter 3

Harmful and nutrient elements in paddy soils and their transfer into rice grains (Oryza sativa) along two river systems in northern and central Vietnam

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Abstract

Thirty soil samples and 24 corresponding unpolished rice samples along the Red and Huong Rivers in northern and central Vietnam respectively, were analyzed in order to evaluate (a) soil geochemistry, (b) factors that determine the transfer of harmful and nutrient elements from soils into rice grains, (c) health risk to the local population through rice consumption. The concentrations of As, Bi, and U in the soils of this area are higher relative to those of average shale probably due to natural redox-related processes. Also, Zn, Ce, Th, La, Sn, Pb, and Cd are accumulated in some soils because of mining activities or industrial wastewater application. Arsenic concentrations exceed the Vietnamese allowable limit of 15 mg kg^{-1} in 80% of the tested soils. Twelve percent of the unpolished rice grains surpass the permissible maximum concentration of 0.2 mg Cd kg^{-1} grain dry matter by FAO/WHO and European Union, and all samples are below the Pb limit. The daily intake of As is within the range of the tolerable intake levels proposed by the European Food Safety Authority. Influences of soil parameters such as pH value, contents of soil organic matter, oxides/hydroxides of Al, Fe, and Mn cause a broad spread of transfer factors from soil to grains. Positive trends exist between the transfer factors within the groups (a) As, Sb, and U, (b) Co, Cu, Ni, and Zn, (c) Cd and Mn which indicate similar influences of soil parameters on their uptake. We propose that the allowable Cd maximum concentration for rice should be set to less than 0.2 mg kg^{-1}. The analysis of As and Cd concentrations in soils and corresponding rice grains as well as the soil pH value should be made obligatory in order to prevent intoxication. In addition, critical elements from nonferrous metal mining and industrial areas should also be evaluated.

Keywords Harmful elements • Nutrients • Paddy soils • Unpolished rice • Human health • Vietnam

3.1 Introduction

Paddy soils along rivers receive suspended materials that are deposited through inundation and/or irrigation. In addition, anthropogenic inputs of potentially harmful elements from air pollution, fertilizers (especially phosphates), agrochemicals, compost, sewage sludge, and manure occur in many areas. Industrial waste, mining, traffic, and energy production contribute to harmful levels of potentially toxic elements in soils, plants, food, fodder and water, and consequently impair human.

Health risks that are associated with the exposure to harmful concentrations of trace elements have been widely investigated. Such risks are dependent on quantity, level of exposure and chemical form of the element, as well as age and gender of the consumer (Vinh et al. 2012). Singh and Kalamdhad (2011) described inorganic As, Cd, and Cr(VI) compounds as carcinogens, which can cause cancer of skin, kidney, lung, liver, or bladder, and bone-weakness. Additionally, these elements can damage flora and fauna, cause weight and yield loss, diminish reproduction rates and increase mortality rates of organisms (Alloway 2013). Synergistic or antagonistic effects of these elements may intensify or reduce the impact.

Rice is Asia´s major staple food crop. More than 90% of the world's rice is produced here (Arunakumara et al. 2013). In countries with preferential rice diet, the composition of rice determines the transfer of beneficial and harmful elements such as Cd and As into the human body (Chaney et al. 2016). An early study by Kobayashi (1978) showed that the Cd contamination around a Zn-Pb mine in Toyama (Japan) caused the Itai-Itai disease of the local population due to intoxication from drinking water and rice consumption. In Hunan Province, China, the mean As concentration in brown rice grains growing near mining areas was found to be 0.52 mg kg^{-1}, which is 2.6 times higher than the FAO/WHO permissible inorganic As level of 0.2 mg kg^{-1} (Fan et al. 2017). In a study in Thailand, 62.5% of white jasmine rice samples and 51.7% of brown jasmine rice samples surpassed the inorganic As limits for rice (Hensawang and Chanpiwat 2017). In most cases, rural communities living in contaminated regions and eating their own rice are exposed to the greatest health risks.

In Vietnam, the Red River area in the north is the second largest rice-cultivating region behind the Mekong River Delta in the south. In 2016, Vietnam produced 43.6 million tons of rice (28.3 million tons of milled rice) on 7.8 million hectares (FAO 2017). The intensification of rice cultivation is likely to lead to a higher concentration of contaminants in rice and soil through increasing use of fertilizers and pesticides (Ahmed et al. 2008). In addition, some agricultural soils close to industrial areas and active mines in Vietnam are highly contaminated. Paddy soils adjacent to mine waste dumps show Pb concentrations of 1271 - 3953 mg kg-1 in Tan Long, Thai Nguyen Province and 250 - 770 mg kg^{-1} dry soil in Chi Dao, Hung Yen Province in northern Vietnam (Chu 2011). In these areas, the Vietnamese allowable Pb level of 70 mg kg^{-1} was exceeded 3 - 56 times. Phuong et al. (2010) identified Cu, Pb, and Zn enrichments in soils close to a copper-casting handicraft village in Hung Yen Province. In Lam Thao, Phu Tho Province in the north, soils irrigated with wastewater also showed high concentrations of Cu (204 mg kg^{-1}), Zn (714 mg kg^{-1}), and Pb (140 mg kg^{-1}) while their Vietnamese permissible limits are 50, 200, and 70 mg kg^{-1} respectively (Vinh et al. 2012). The mean concentrations of As, Cd, and Pb in unpolished rice at these sites surpassed 2 - 4 times the allowable limit of 0.2 mg kg^{-1} of each element. In paddy fields along To Lich and Kim Nguu Rivers in Ha Noi Province, the mean concentrations of Cd (4 mg kg^{-1}), Cu (202 mg kg^{-1}), Pb (159 mg kg^{-1}), and Zn (192 mg kg^{-1}) were higher than the allowable soil limits of 2, 50, 70, and 200 mg kg^{-1} respectively (Huong et al. 2008). The mean content of Cr (3.1 mg kg^{-1}) and Pb (2.1 mg kg^{-1}) in rice grains of these fields exceed the permissible limit of 1 and 0.2 mg kg^{-1} respectively.

The goal of this study is to evaluate (1) the soil composition and enrichment of potentially harmful elements in paddy soils in relation to geogenic background values, (2) the influence of soil factors on the transfer of elements from soil into the rice grain, (3) the daily intake of elements through rice consumption in relation to the daily demand for nutrient elements and the tolerable upper intake levels for potentially toxic elements.

3.2 Materials and methods

3.2.1 Study area

Paddy soils and corresponding rice samples were collected in September 2015 along the Huong River in central Vietnam and the Red River in northern Vietnam (Fig. 3.1). Five locations were chosen along the Huong River, where the impact of industrial and mining activities is low. The remaining 25 locations were along the lower Red River, which showed some anthropogenic influences. For instance, the samples HN5 to HN9 were taken in the surroundings of a brick factory, PT5 to PT9 near a fertilizer and chemical factory, PT2 and PT4 at the Red River bank.

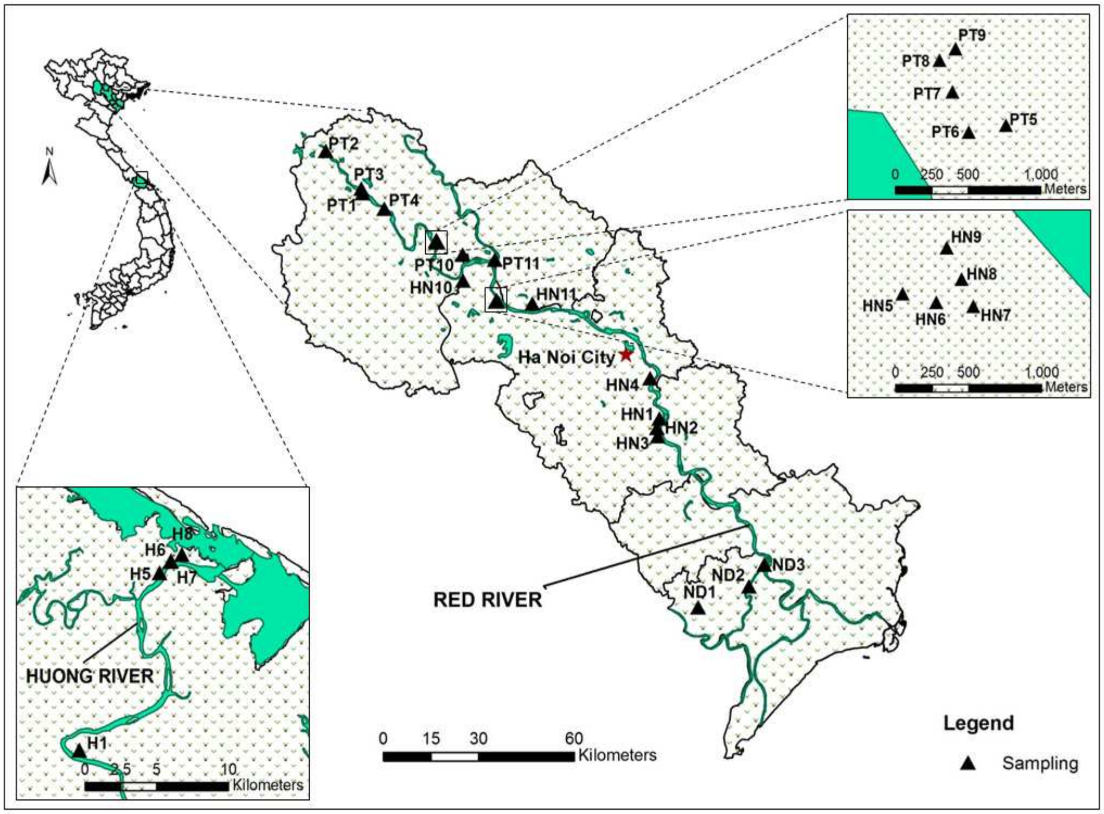

Fig. 3.1 Map of sample locations in central and northern Vietnam

3.2.2 Sampling, preparation, analysis and calculation

The soil samples were collected in the rooting zone of the rice plants, which is at 0 - 10 cm depth. All soil and rice samples were taken within ten days before the typical rice harvesting time. The samples were air-dried and transported to Germany. Soil samples were dried at 105°C, and rice samples at 60°C in the laboratory of the Geoscience Center of Göttingen University. All samples were pulverized to particle sizes <63 µm by an agate ball mill (Fritsch Pulverisette 5) and the grain samples were ground by hand with an agate mortar. Soil pH was measured in a 1:2.5 mixture of air-dried soil and 0.01 M $CaCl_2$ solution by using a glass electrode WTW ProfiLine pH/mV-Meter 197. To quantify element concentrations in the soil and rice grain samples, 150 mg of pulverized soil and 700 mg of grain power were completely digested in a mixture of the ultrapure concentrated acids HNO_3, HF, and $HClO_4$ in a closed ultra-clean PTFE vessel (PicoTrace®, Bovenden, Acid Sample Digestion System DAS 30). To dissolve precipitated aluminum and iron oxides/hydroxides, a small amount of HCl was added in the last step of the soil digestion procedure. The resulting clear solutions were diluted to 100 ml and 50 ml for soil and plant samples respectively. In addition, blank (only acids without sample material) and reference samples were included into every digestion series. The elements in the solution were quantified by Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) Agilent 5100 VDV and by Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) Thermo Scientific iCAP Q. The reproducibility and accuracy of measurements were checked by an in-house and international reference rock (Wissenbach slate TW45; lake sediment GSJ-JLk-1) and reference plant materials (Bush branches and leaves NCS DC 73349; maize plant WEPAL-IPE-126). The detailed results of the reference samples, and the selected wavelength (ICP-OES) and mass (ICP-MS) that were used for every element are listed in Tables A1.1 in Appendix A1. For most elements, the deviation from certified values was smaller than 5%.

Loss on ignition (LOI) is used as a proxy for the content of organic matter and of water in clay mineral, and oxides/hydroxides in the soil. The LOI was determined as the weight loss by heating 500 mg of the milled soil samples to 530°C for 2 hours. The approximate SiO_2 concentration was calculated as follows:

$$SiO_2 = [100 - (\text{main element oxides} + \text{minor element oxides} + \text{LOI})] \qquad (\text{wt. }\%)$$

3.3 Results and discussion

3.3.1 Soil geochemistry

The parent materials of the analyzed paddy soil samples in the Red River area are mainly alluvial sediments of the Yunnan Plateau and of the surrounding highlands. The Huong River transports mainly eroded material from the Annamite Range. Descriptive statistics of the concentrations of selected elements in the analyzed paddy soils, the average shale and Earth crust are listed in Table 3.1. A single dataset of every sample is provided in Table A1.2 in Appendix A1.

The soils contain more water and organic matter compared to rock materials. The average LOI value for the soils is 6.6%, which suggests that element concentrations on an LOI-free basis would be higher by a factor 1.066. However, this aspect is not considered in this study.

Because of the lack of geochemical data on the parent material in the drainage basins of the two rivers, the soil data are compared with the average composition of shale or Earth crust as reference. The ratios of the median element concentration in soil El_{soil} to the mean element concentration in shale El_{shale} are given in Table 3.1. The following trends of element depletion or enrichment are typical for the investigated soils from both areas:

- Depleted elements (decreasing depletion): Ca, S, Mg, Ni, Li, Sr, Mn, Na, K, Mo, Cr, Ba, Hf, Co, V, Zr, Fe, Sb
- Elements with changes less than 10%: Cu, Tl, Sc, Rb, Al, Ga, Ti, Si
- Enriched elements (increasing enrichment): P, Ce, Cs, Th, U, La, Nb, Sn, Pb, As, Cd, Bi.

Losses of Ca, Mg and Na result from chemical weathering, soil acidification, and anthropogenic activities such as agricultural practices. Low soil pH and deficiency of Ca and Mg in soils do not only decrease crop yield, but also increase the susceptibility of plants to trace metal uptake (Gransee and Führs 2013). The soil pH values along the Huong River range from 4.2 to 4.7, which are lower than those in the Red River soils with most pH values >5.5. Lower pH values coincide with the low concentrations of Ca, Na, and Mg in the Huong area. Thus, the soil pH-buffering and fertilizing elements are widely missing in the Huong area. The SiO_2 concentration is high in this area because of the high presence of quartz.

The median concentrations of some elements are considerably higher than the average shale concentrations (Sn 1.9 times, Pb and As 2.0 times, Bi 4.6 times). The accumulation of As is caused by natural redox processes and can be explained by the following steps (Fendorf and Kocar 2009, Polizzotto et al. 2008):

- Uplifting, weathering, and erosion of rocks in the mountains and oxidation of Fe^{II}- and As^{III}-bearing sulfides
- Oxidation of these Fe and As compounds, precipitation of Fe^{III} oxides/hydroxides and sorption of As^{V}
- Transportation and deposition of suspended material, including As-rich Fe-phases in river systems and paddy fields
- Reduction of the As-containing Fe-phases forming dissolved Fe^{II} and As^{III} in anaerobic soils of rice fields, facilitating the uptake of As by rice plants.

A similar natural enrichment mechanism might be applicable to Bi.

Table 3.1 Statistics on selected element concentrations in the studied soils (n = 30) in comparison with average shale, Earth crust, and maximum allowable limit in agricultural soil (main elements from LOI to SiO_2 in wt. %, and trace elements in mg kg^{-1} dry matter)

Element	Min	Q1	Median	Q3	Max	Mean	Stdev	Shale	Earth crust	El_{soil} / El_{shale}	Allowable limits
pH	4.2	5.1	5.9	6.7	7.3	5.9	1.0	-	-		-
LOI	3.5	5.2	6.5	7.2	11.1	6.6	1.9	-	-		-
Al_2O_3	7.4	12.4	15.1	16.3	18.3	14.4	2.7	15.1[a]	15.4[c]	1.00	-
CaO	0.29	0.43	0.56	0.88	2.08	0.72	0.43	3.3[b]	3.59[c]	0.17	-
Fe_2O_3	2.8	5.2	6.0	6.5	13.1	6.2	2.1	6.9[d]	5.0[c]	0.87	-
K_2O	1.00	2.2	2.5	2.8	3.2	2.4	0.51	3.8[b]	2.8[c]	0.66	-
MgO	0.54	1.00	1.35	1.61	1.93	1.28	0.39	2.7[d]	2.5[c]	0.51	-
MnO	0.027	0.042	0.062	0.081	0.116	0.063	0.025	0.11[d]	0.10[c]	0.56	-
Na_2O	0.27	0.43	0.66	0.73	1.51	0.65	0.26	1.01[b]	3.3[c]	0.65	-
P_2O_5	0.09	0.14	0.19	0.22	0.47	0.19	0.07	0.16[a]	0.15[c]	1.19	-
S	0.016	0.030	0.045	0.061	0.87	0.090	0.176	0.24[a]	0.056[c]	0.19	-
TiO_2	0.54	0.75	0.83	0.88	0.92	0.81	0.09	0.77[d]	0.64[c]	1.08	-
SiO_2	56.0	62.0	66.6	69.0	81.2	66.6	6.1	60.5[b]	66.6[c]	1.10	-
As	9.5	15.9	19.8	24.2	49.7	21.9	10.0	10.0[d]	4.8[c]	1.98	15.0[e]
Ba	159	378	428	455	815	423	108	636[b]	624[c]	0.67	-
Bi	0.22	0.46	0.60	0.79	3.7	0.84	0.79	0.13[d]	0.16[c]	4.62	-
Cd	0.17	0.30	0.34	0.45	6.5	0.56	1.12	0.13[d]	0.09[c]	2.62	1.50[f]
Ce	55	79	89	97	184	91	26	67[b]	63[c]	1.33	-
Co	7.3	13.7	15.9	19.0	49.6	16.5	7.3	19.0[d]	17.3[c]	0.84	20-50[e]
Cr	30	48	60	77	128	64	24	90[d]	92[c]	0.67	150[f]
Cs	3.2	6.0	7.4	10.4	12.0	7.8	2.5	5.2[b]	4.9[c]	1.42	-
Cu	20	37	41	52	885	72	154	45[d]	28[c]	0.91	100[f]
Ga	10	17	20	23	27	20	4	19[a]	17.5[c]	1.05	-
Hf	1.6	3.5	4.3	4.7	5.0	4.0	0.9	6.3[b]	5.3[c]	0.68	-
La	27	38	45	47	90	44	11	31[b]	31[c]	1.45	-
Li	18	30	36	47	56	38	12	66[a]	21[c]	0.55	-
Mo	0.41	0.68	0.86	1.26	2.50	1.04	0.56	1.3[d]	1.1[c]	0.66	4-10[e]
Nb	13	18	21	23	38	21	5	11[a]	12[c]	1.91	-
Ni	19	32	37	48	58	38	11	68[d]	47[c]	0.54	20-60[e]
Pb	23	35	43	58	86	48	18	22[d]	17[c]	1.95	70[f]
Rb	49	107	124	139	164	118	27	125[b]	84[c]	0.99	-
Sb	1.0	1.6	1.9	2.2	3.5	2.0	0.6	2.1[b]	0.4[c]	0.90	10[e]
Sc	6.1	11.2	14.2	15.3	18.8	13.4	3.0	14.9[b]	14[c]	0.95	
Sn	3.3	3.9	4.8	5.3	8.0	4.8	1.1	2.5[d]	2.1[c]	1.92	50[e]
Sr	30	51	78	82	170	74	28	142[b]	320[c]	0.55	-
Th	9.1	16.0	17.6	19.3	29.9	17.8	3.6	12.3[b]	10.5[c]	1.43	-
Tl	0.31	0.53	0.62	0.71	0.81	0.60	0.13	0.68[d]	0.90[c]	0.91	-
U	2.8	3.5	3.9	4.2	6.7	4.0	0.8	2.7[b]	2.7[c]	1.44	-
V	55	92	110	123	165	109	25	130[d]	97[c]	0.85	-
Zn	64	86	107	129	1725	160	297	95[a]	67[c]	1.13	200[f]
Zr	47	109	136	148	154	125	29	160[a]	193[c]	0.85	

[a]Turekian and Wedepohl (1961); [b]Gromet et al. (1984); [c]Rudnick and Gao (2003); [d]Wedepohl (2004); [e]Kabata-Pendias (2011); [f]QCVN (2015): The Vietnamese guideline for agricultural soil. For the ratio El_{soil} / El_{shale} the median concentration in soil is divided by average shale concentration.

The presence of Fe oxides/hydroxides is shown in studies by Postma et al. (2012, 2016) and Sø et al. (2018), who analyzed various sediments that were deposited along the Red River. They identified in suboxic to anoxic sediments under inert N_2 atmosphere, strongly varying Fe-oxide concentrations between 1 and 77 µmol/g Fe (corresponding to 0.008 to 0.61 wt. % Fe_2O_3), with the highest concentrations in the most recent sediments. The authors calculated that some of the Fe^{II} might exist as siderite ($FeCO_3$). In the younger sediments the ratios As to Fe (bound as oxide) are fairly stable at 1.2 mmol/mol, which corresponds to 1126 mg As kg^{-1} Fe_2O_3. Similar solution precipitation dynamics are assumed for the paddy soils that are investigated in this paper.

The enrichment of Pb and Cd has different anthropogenic sources (emission and fertilizers). Both elements are deposited from the atmosphere and from contaminated river suspension in the irrigation water used. Cadmium may have been additionally accumulated through the application of phosphate fertilizer (Chen and Graedel 2015; Kratz et al. 2016). The paddy soils along Huong River in central Vietnam are less affected by anthropogenic activities compared to those along the Red River in the north. The Red River soils have higher Cd and Pb concentrations and slightly elevated contents of As, Bi, Cr, Cu, Ni, P, Zn, Mn, and Fe (see Table A1.2 in Appendix A1). Reasons might be the higher content of Fe- and Mn-oxides/hydroxides enriched with these elements.

Some sites contain extraordinarily high concentrations of various elements (detailed data in Table A1.2 in Appendix A1):

- Soils sampled at PT2 and PT4, which were taken close to the Red River, show strong enrichments of Ca, Mg, Na, As, Bi, Cd, Cu, Mn, Pb, Sb, Sn, Zn, and of some rare-earth elements like La and Ce. These elements may be accumulated over time through river-transported materials. Considering that there are mining activities along the upper Red River, these enrichments might be caused by the exploitation of the Adebo monazite (Ce[PO4]) mine in Jinping (Xie et al. 2016), the Yuanjiang Gold Mine, Gejiu Tin Mine, and Laojinshan Gold Mine in the mountains south of Dali in China`s Yunnan Province (Yang et al. 2014). Soil contamination around these mines might deliver additional contamination via the Yuan River into the Red River.
- Soils sampled at PT5, PT6, and PT7 were taken within a radius of 700 meters around Lam Thao fertilizer and chemical factory. During sampling, the soil surfaces were covered by 50 cm of water, which was unusually high. PT5, PT6, and PT7 contain

9.2, 13.1, and 11.4% Fe_2O_3 respectively, which are nearly twice as much as the median value of the other soil samples. One reason for such elevated concentrations can be the discharge of iron-rich municipal wastewater on these sites (Kabata-Pendias 2011). In these soils, Cr reaches extreme values of 109, 200, and 194 mg kg^{-1} respectively. One reason can be the discharge of polluted municipal wastewater. In addition, PT5 is strongly enriched in As, Cd, Cu, Pb, Zn, Co, Mo, U, LOI, and S, what is possibly caused by the contaminated effluents from the factory. Portions of these elements (including Fe) are probably bound as sulfides with the exception of Ce, La, and U.

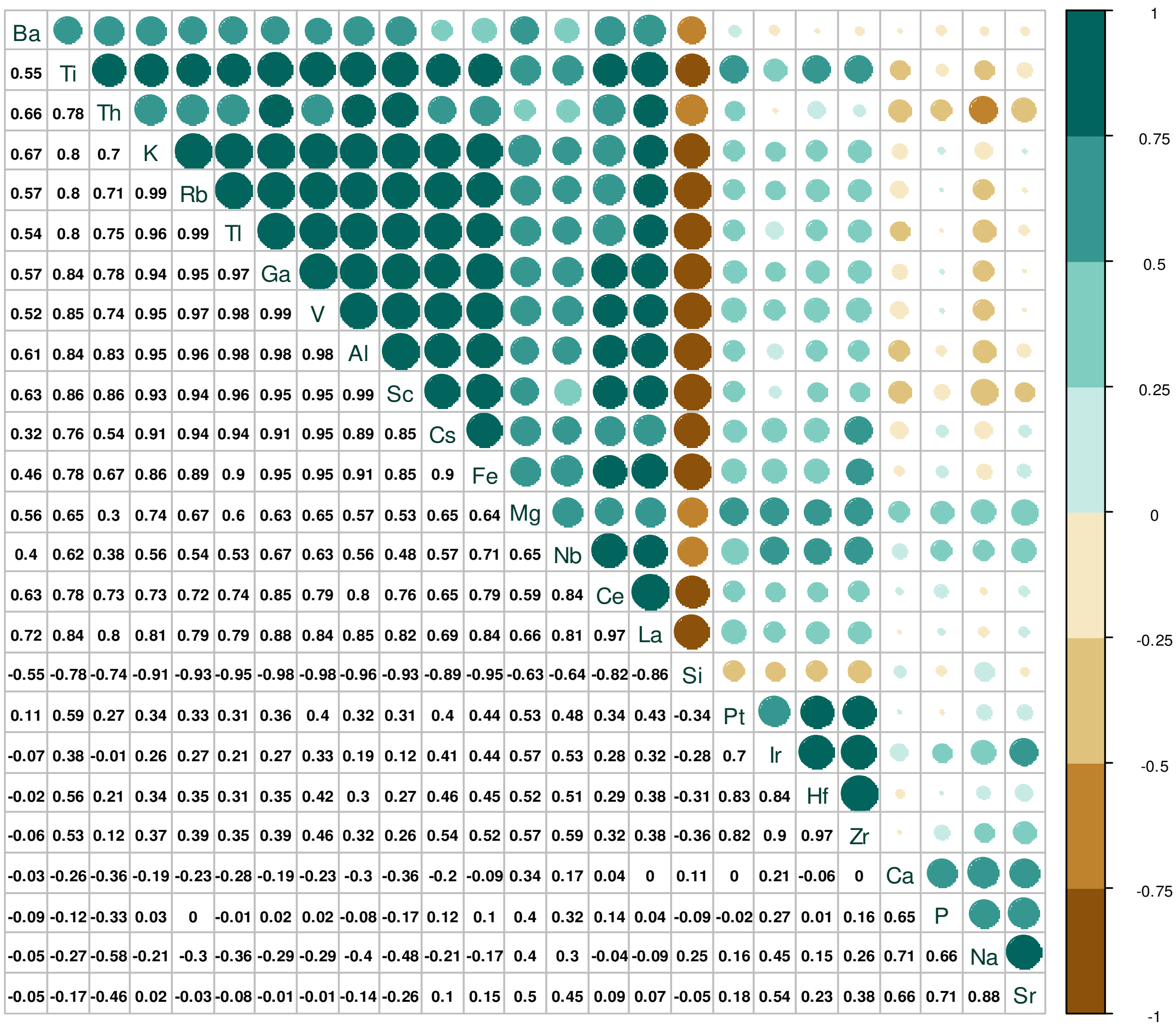

Fig. 3.2 Correlation matrix of soil element concentrations with no or negligible human influence. Diameter and color of the circles change with the value of the correlation coefficient

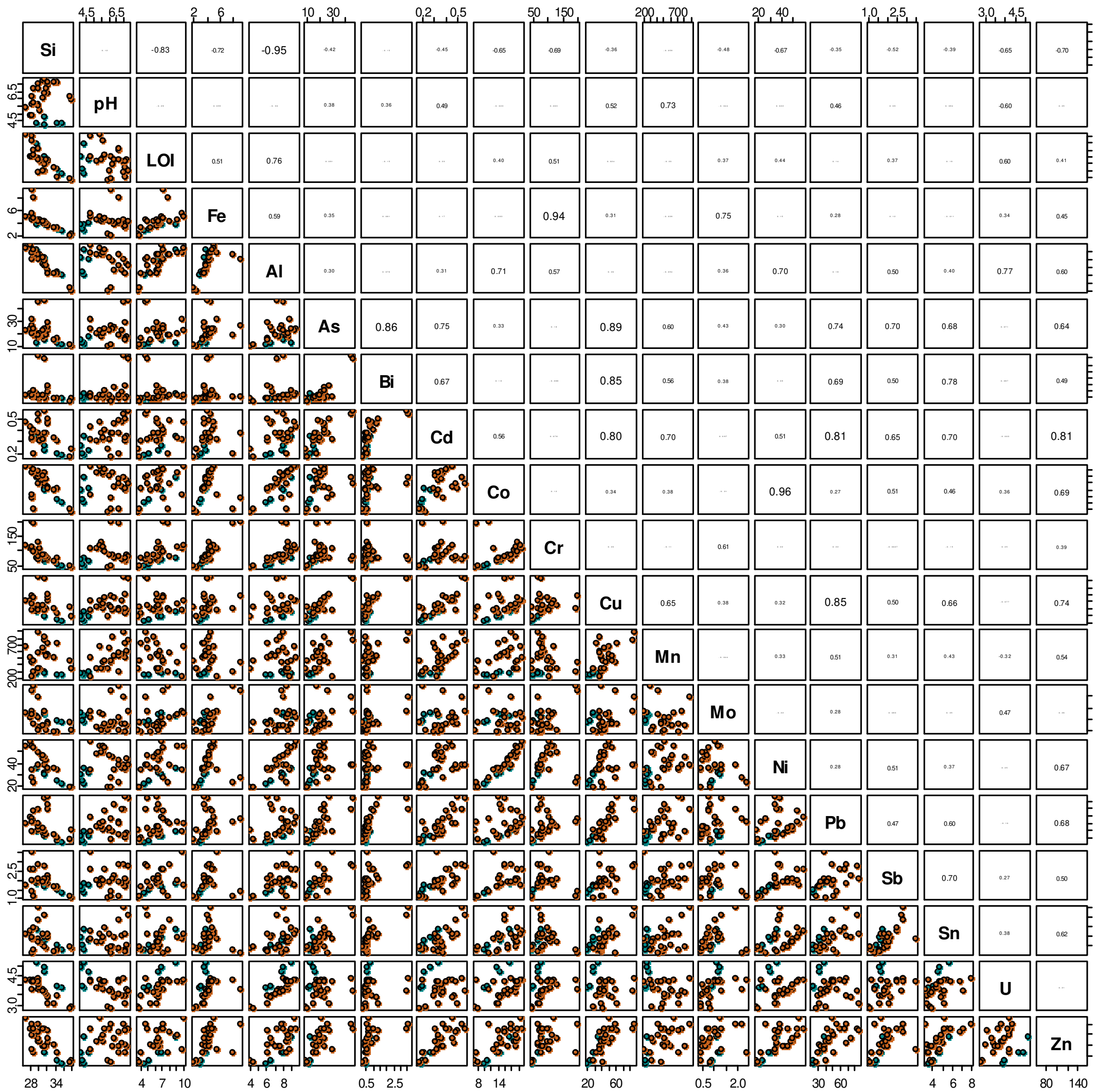

Fig. 3.3 Correlation plots of trace element concentrations in soils (site PT5 and sulfur in PT10 are excluded). Blue dots represent samples from the Huong River, red dots samples from the Red River

To get further information on the association of elements within soils, Pearson product-moment correlation coefficients for element concentration pairs are calculated. Elements, which are not or only slightly influenced by man, are visualized in Fig. 3.2. They are selected if the shale-normalized element ratio is less than or equal to 1 as shown in Table 3.1. There are four element groups with significant positive correlation coefficients:

- The first group comprises the elements Ba, Ti, Th, K, Rb, Tl, Ga, V, Al, Sc, Cs, Fe, Mg, Nb, Ce, and La. All these elements are enriched in clay minerals and/or Fe oxides/hydroxides, which are often intimately associated in soils and sediments. Their negative correlation with Si is due to the increased concentrations of quartz (SiO_2) and bio-opal ($SiO_2.nH_2O$). These phases dilute the other elements, which cause their positive correlations. The elements K, Rb, Al, Fe, Sc, La, Ga, and V form a subgroup with very high correlation coefficients of $r > 0.8$. Al and Fe have a correlation coefficient of $r = 0.91$, whereby the extreme Fe-rich samples PT5, PT6 and PT7 were excluded.

- The second group comprises Hf and Zr with $r = 0.97$. Their strong correlations can be explained by their comparable parent material, poor mobility in soil, and dilution with quartz. They are bound in their own weathering-resistant phases.
- The third group contains the highly correlated elements Ca, P, Na, and Sr. These elements are fairly mobile during weathering, but they are also added by phosphate and lime fertilizers (except for Na).
- LOI shows a positive correlation with S and to a certain degree with Al and Fe that have water bound phases. Sulfur is usually enriched in organic material or as sulfide in reducing environments (as assumed for the sites PT5 and PT10).

The elements Co, Cr, Cu, Mo, Ni, and Sb are not enriched relative to shale. However, they are plotted in Fig. 3 because they belong to the potentially toxic elements group as listed by Alloway (2013). The correlations between the concentrations of these critical elements are plotted against each other in Fig. 3.3. Many of these elements such as As, Cd, Co, Cr, Cu, Mo, Ni, Pb, Sb, U, and Zn have positive correlations with Al and Fe. Reasons are that the nearly amorphous Al- and Fe-rich weathering phases are able to accumulate these critical elements by sorption and co-precipitation (Lair et al. 2007; Young 2013). Manganese shows only slight correlations with the other trace elements. Presumably, oxidic Mn-phases are not present due to the low oxidation speed of Mn^{2+} during aeration of paddy soils. Excluding some specific samples with stronger enrichments, some elements show remarkable correlations with each other: group 1 - Co, Ni, Cr; group 2 - As, Bi, Cu, Pb; group 3 - Zn, Cd, Sb. The elements of group 1 may have similar concentration ratios in the parent material, and their geochemical behavior is similar. The elements in group 2 and 3 are additionally affected by the redox behavior of Fe in the paddy fields during the growing season (release of the elements during reduction of Fe-oxides/hydroxides and sorption/co-precipitation during oxidation events).

Most element concentrations in the analyzed paddy soils are within the Vietnamese national technical regulation on the allowable limits of heavy metals in the soils (QCVN 2015) except for As. 80 % of the samples exceed the As concentration limit of 15 mg kg^{-1} in; 13% surpass the limit by more than a factor of 2. The median As concentration of 19.8 mg kg^{-1} is considerably higher than those of agricultural soils in the U.S. and Europe with 7.2 and 5.5 mg kg^{-1} respectively (Kabata-Pendias 2011; Reimann et al. 2018). In addition, sample PT5 located near the fertilizer and chemical factory exceeds the allowable levels for Vietnamese agricultural soil for As by factor 3.3, Cd by 4.3, Cu by 8.9, Pb by 1.1, and Zn by 8.6.

3.3.2 Transfer of elements from soil into unpolished rice

Descriptive statistics of the concentrations and transfer factors of nutrients and potentially harmful elements in unpolished rice are shown in Table 3.2 (the detailed values are listed in Table A1.3 and A1.4 in Appendix A1). To evaluate the transport ability of elements from soil to rice grains, transfer factors (TF) are calculated (Table 2) according to:

$$TF = El_{rice\ grain} / El_{soil}$$

In which $El_{rice\ grain}$ refers to element concentration in rice grains, El_{soil} to the corresponding soil concentration (Sauer & Ruppert 2013).

Table 3.2 Concentrations and transfer factors of selected elements in unpolished rice (n=24)

Elements	Concentration (mg kg^{-1})					Transfer factors				
	Min	Median	Max	Mean	Stdev	Min	Median	Max	Mean	Stdev
Al	<4	<4	15.4	<4	-	<0.00005	<0.00005	0.00020	<0.00005	-
Ca	106	135	163	135	14	0.008	0.029	0.073	0.035	0.018
Fe	8.3	11.0	19.3	11.3	2.4	0.0001	0.0003	0.0005	0.0003	0.0001
K	2356	2966	3352	2916	263	0.10	0.15	0.36	0.16	0.06
Mg	1104	1381	1591	1368	134	0.11	0.19	0.42	0.20	0.07
Mn	12	22	45	22	6	0.015	0.042	0.22	0.059	0.043
Na	2.7	3.9	8.4	4.4	1.5	0.0004	0.0010	0.0032	0.0012	0.0008
P	2656	3613	4167	3519	385	2.0	4.7	8.5	4.7	1.5
S	884	1086	1330	1090	121	0.1	2.4	6.5	2.8	1.6
Ti	<0.05	0.06	0.86	<0.1	-	<0.00001	0.00001	0.0002	<0.00002	-
As	0.11	0.21	0.34	0.22	0.08	0.002	0.010	0.027	0.012	0.006
Ba	0.44	1.20	3.6	1.30	0.65	0.001	0.003	0.009	0.003	0.002
Bi	<0.0002	0.0002	0.0045	0.0005	0.0009	<0.0003	0.0004	0.0057	0.0006	0.0014
Cd	0.002	0.042	0.96	0.111	0.199	0.005	0.124	2.99	0.35	0.62
Ce	<0.0006	0.0008	0.0144	0.0016	0.0029	<0.00001	0.00001	0.00014	0.00002	-
Co	0.004	0.020	0.133	0.028	0.029	0.0002	0.0010	0.0134	0.0020	0.0028
Cr	<0.1	<0.1	<0.1	<0.1	-	<0.001	<0.001	0.003	<0.001	-
Cs	0.005	0.030	0.99	0.103	0.21	0.0005	0.0037	0.202	0.0192	0.043
Cu	0.72	3.3	8.5	3.4	1.61	0.003	0.086	0.23	0.085	0.051
Hf	<0.0002	<0.0002	0.0015	<0.0004	-	<0.00005	<0.00005	0.0003	<0.0002	-
La	<0.0003	0.0004	0.0079	0.0009	0.0016	<0.00001	0.00001	0.00017	0.00002	-
Li	<0.006	<0.006	0.03	<0.008	-	<0.0001	<0.0001	0.001	<0.0002	-

Mo	0.18	0.57	1.29	0.63	0.32	0.09	0.92	3.1	0.90	0.69
Nb	<0.034	<0.034	<0.034	<0.034	-	<0.002	<0.002	<0.002	<0.002	-
Ni	0.03	0.35	2.24	0.45	0.49	0.001	0.009	0.104	0.015	0.022
Pb	<0.02	<0.02	<0.02	<0.02	-	<0.0005	<0.0005	0.0005	<0.0005	-
Rb	2.6	11.5	60.2	18.4	15.7	0.02	0.10	0.62	0.19	0.18
Sb	<0.0006	<0.0006	<0.0006	<0.0006	-	<0.0003	<0.0003	0.0006	<0.0003	-
Sc	<0.003	<0.003	0.005	<0.003	-	<0.0003	<0.0003	0.0003	<0.0003	-
Sn	<0.06	<0.06	<0.06	<0.06	-	<0.02	<0.02	<0.02	<0.02	-
Sr	0.18	0.38	0.53	0.38	0.09	0.002	0.005	0.015	0.006	0.004
Th	<0.0002	<0.0002	0.0025	<0.0002	-	<0.00001	<0.00001	0.00011	<0.00001	-
Tl	<0.0002	0.0002	0.0004	0.0002	0.0001	<0.0003	0.0004	0.0009	0.0004	-
U	<0.0001	<0.0001	0.0017	<0.0001	-	<0.00002	<0.00002	0.0003	<0.00005	-
Zn	13.7	24.6	32.2	24.0	4.1	0.02	0.23	0.37	0.23	0.08
Zr	<0.007	<0.007	0.066	<0.007	-	<0.00006	<0.00006	0.0005	<0.00006	-

Most of the element concentrations in unpolished rice are not or only slightly correlated with each other except for K, Mg, and P with correlation coefficients higher than 0.7 (Fig. A1.1 in Appendix). Mg and P concentrations in unpolished rice show an outstanding correlation:

$$[P] = 2.7 * [Mg] - 172 \quad (r = 0.94)$$

The concentrations of As, Bi, Ca, Cd, Co, Cu, Fe, Mn, Na, Ni, P, Sb, and Zn in most grain samples of the central area are higher compared to those in the northern area. This trend is opposite to the soil concentrations (compare Table A1.2 and Table A1.3 in Appendix A1). A master variable for element transfer into plants is the pH value of the soil. In the central area, soil pH values range from 4.2 to 4.7, in the northern area from 4.8 to 7.3. Soil pH affects element transfer by two mechanisms:

- Many cationic elements get soluble in acidic solution (desorption from surface sites at pH values < 5) and insoluble under weakly acidic to slightly alkaline conditions (sorption maximum between pH 5 and 8).
- Acidification increases the solubility of the sorbents Al-, Fe-, and Mn-oxides/hydroxides, thus enforcing the release of elements into solution.

In addition, under low Eh conditions and absence of sulfur, most of the cationic heavy metals including As, Bi and Sb could go into solution because Fe-oxides/hydroxides are dissolved. This release facilitates the uptake of these elements by the rice plant. On the other hand, sorption on organic material may lower the concentration of dissolved elements hindering their uptake.

The concentrations of elements in unpolished rice show no significant correlations with their corresponding soil concentrations except for phosphorus. To visualize the relative ability of the plant to mobilize and take up elements from the soil, transfer factors (TFs) are plotted in

Fig. 3.4. Mean TFs are presented in a decreasing order (elements in brackets have median concentrations in grains below detection limit):

- TF 5 to 1: P, S
- TF 1 to 0.1: Mo, Zn, Mg, K, Cd
- TF 0.1 to 0.01: Rb, Cu, Mn, Ca, (Sn), As
- TF 0.01 to 0.001: Ni, Sr, Cs, Ba, (Nb), Co
- TF <0.001: (Cr), Na, Bi, Tl, Fe, (Pb), (Sb), (Sc), (Zr), (Hf), (U), La, Ce, (Li), (Al), (Ti), (Th)

There is a broad variation of TFs for some elements, which spans over 3 orders of magnitude for Cd (from 0.01 to 3), but only 1 order of magnitude for the nutrients K, Mg, P, Fe, and Zn.

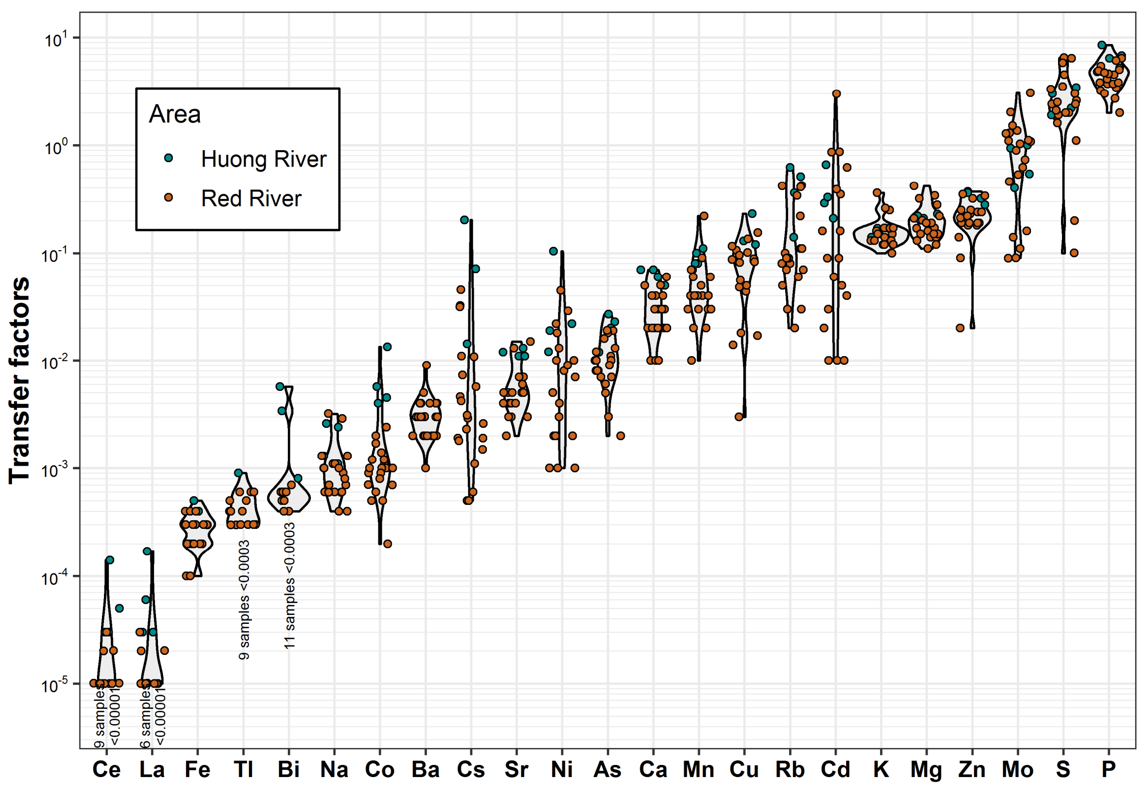

Fig. 3.4 Transfer factors of some elements from soil into rice grain. TFs of elements with concentrations below detection limit are not shown: Th, Ce, La, Al, U, Zr, V, Sb, Pb, Ti, Cr, Sn, Co

Reasons for the broad TF variation and the lack of correlation between soil and plant concentrations are influences of various soil and plant factors. The most important soil factors are the pH- and Eh-value in the soil solution, the concentration of organic matter, Al- and Fe-oxides/hydroxides, and clay minerals. These parameters influence binding, distribution, and availability of elements in soils. The concentration and species of an element in soil solution determine the element uptake by a plant root. Within plants, different element distribution and incorporation mechanisms lead to different concentrations in different parts of the plant (Greger 2004).

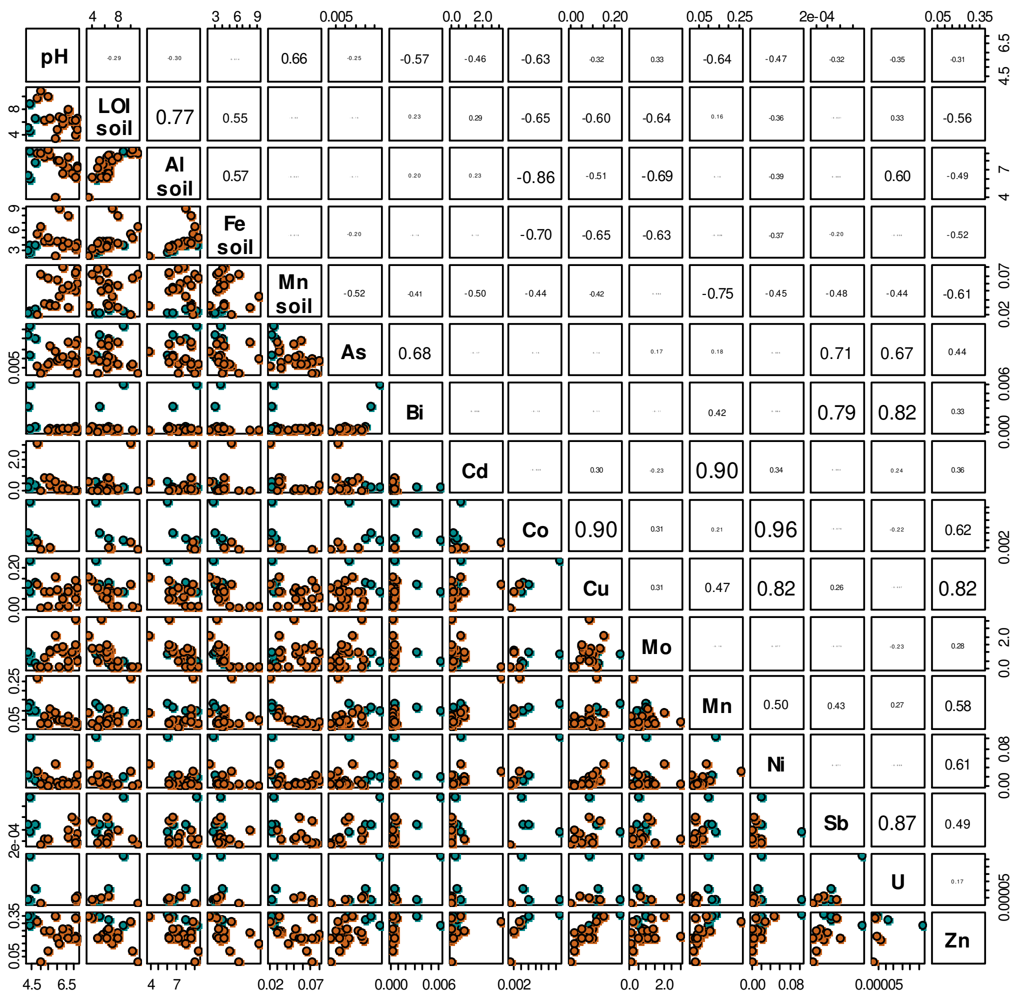

Fig. 3.5 Correlation plots of the soil parameters pH, LOI, Al, Fe, and Mn (wt. %) with transfer factors of potentially toxic elements. Blue dots represent samples from the Huong River, red dots samples from the Red River

In this context, the TFs of sample site PT5 are remarkable. As described above, various potentially toxic elements are strongly enriched in the soil. The rice grains, however, show element concentrations that are typical for uncontaminated sites. One reason for the little uptake at site PT5 may be the reducing environment within the soil, which is indicated by the outstanding concentrations of organic matter (LOI 11.1%), Fe_2O_3 (9.2%), S (0.87%), and P_2O_5 (0.47%). In the stagnant anoxic interstitial water, sulfide ions may form insoluble compounds with most of the divalent cationic heavy metals as well as As, Sb, and Bi. Another mechanism could be the sorption of the elements on organic matter and the precipitation of cationic elements as insoluble phosphates. These fixation mechanisms may inhibit a trace element transfer into the rice plant.

In Fig. 3.5, TFs of different potentially toxic elements are plotted against each other, soil pH values, and concentrations of LOI, Al, Fe, and Mn. As expected, sites with low pH values between 4 and 5 tend to increased TFs of As, Bi, Cd, Co, Mn, Ni, Sb and Zn, but sites with pH > 5 to lowered TFs. As, Mo, and Sb tend to higher TFs at pH > 6. In the presence of oxygen, these elements form oxy-anions. At higher pH values, OH-ions may replace the oxy-anions at the oxide/hydroxide interfaces and release them into solution for uptake by plants.

The TFs of As, Co, Cu, Mo, Mn, Ni, Sb, and Zn show slightly downward trends with increasing concentrations of LOI, Al-, Fe-oxides/hydroxides, and clay minerals in soils. These soil compounds hamper the plant's uptake of these elements. In contrast, the TF of U increases with rising concentrations of LOI and Al-phases. An explanation may be that U is loosely sorbed on clay minerals or organic matter from which it may be easily desorbed. Looking at the plots of TFs, similar uptake trends within three element groups become evident: group 1 - As, Sb, and U; group 2 - Co, Cu, Ni, and Zn; group 3 - Cd and Mn.

3.3.3 Intake of nutrient and harmful elements by eating rice

Rice is the most important energy supplier for the Vietnamese population. Therefore, it is of great importance to get information on the amount of beneficial and harmful elements taken up by human through rice consumption. In rural areas of Vietnam, people older than 19 years eat on average 0.398 kg rice per day: female 0.35 kg day^{-1} and male 0.45 kg day^{-1} (based on information from local population). The daily intake of nutrient and toxic elements is calculated by multiplying the daily amount of rice consumed (kg day^{-1}) by the element concentration in rice (mg kg^{-1}). Table 3.3 shows the intake quantities compared with the Daily Recommended Dietary Allowances (RDA) and Tolerable Upper Intake Levels (UL) for human issued by Food and Nutrient Board (FNB) of the U.S National Academies (Institute of Medicine 2001) and the European Food Safety Authority (EFSA various years).

The average element intake for some nutrient elements from rice is higher as compared to the total recommended dietary allowances: Mn 4.4 times, P 1.8 times, Mg 1.5 times, Mo 4.4 times, and Cu 1.3 times. However, the values of these elements are far below the ULs of EFSA with the exception of Mg, which is 1.4 times higher than UL, and Mn in some areas. In contrast, the Ca and Fe supply by rice consumption is far below people's daily requirement. The low supply of these elements must be complemented by other food products and water.

Table 3.3 Daily element intake for a Vietnamese adult by eating rice in comparison with the Daily Recommended Dietary Allowances (RDA) and the Daily Tolerable Upper Intake Levels (UL) for total consumption of food and drinking water in mg day^{-1} (Institute of Medicine 2001 and other sources)

Element	Intake by Female					Intake by Male				
	Study area			FNB		Study area			FNB	
	Min	Max	Mean	RDA	UL	Min	Max	Mean	RDA	UL
Ca	37	57	47	1000	2500	47	73	60	1000	2500
Fe	3	7	4	18	45	4	9	5	8	45
K	825	1173	1020	-	-	1051	1495	1300	-	-
Mg	386	557	479	310	350	492	710	610	400	350
Na	0.9	2.9	1.6	-	2300	1.2	3.7	2.0	-	2300
Zn	5	11	8	8	40	6	14	11	11	40
P	930	1458	1232	700	4000	1184	1858	1569	700	4000
As	0.04	0.12	0.08	-	0.096[a]	0.05	0.15	0.10	-	0.124[a]
Cd	0.001	0.34	0.039	-	0.016[a]	0.001	0.43	0.049	-	0.021[a]
Cr	<0.04	<0.04	<0.04	0.025	-	<0.05	<0.05	<0.05	0.035	-
Co	0.001	0.05	0.01	-	0.072[a]	0.002	0.06	0.01		0.093[a]
Cu	0.3	3.0	1.2	0.9	10	0.3	3.8	1.5	0.9	10
Mn	4	16	8	1.8	11	5	20	10	2.3	11
Mo	0.06	0.45	0.22	0.05	2.0	0.08	0.58	0.28	0.05	2.0
Ni	0.01	0.78	0.16	-	1.0	0.01	1.00	0.20	-	1.0
Pb	<0.007	<0.007	<0.007	-	0.067[a]	<0.009	<0.009	<0.009	-	0.087[a]
Sb	<0.0002	<0.0002	<0.0002		0.27[b]	<0.0003	<0.0003	<0.0003		0.35[b]
Sn	<0.02	<0.02	<0.02	-	90[a]	<0.03	<0.03	<0.03		116[a]
U	<0.00004	0.0006	<0.00004	-	0.03[a]	<0.00004	0.0007	<0.00004	-	0.04[a]

[a] calculated from tolerable weekly intake doses issued by the European Food Safety Authority (EFSA, various years) for average Vietnamese female and male; [b] calculated from data of van Leeuwen and Aldenberg (2012)

The intake of the critical elements Sn, As, Cd, U, Pb, Co, and Sb is compared with the ULs given by the EFSA (various years) and van Leeuwen and Aldenberg (2012). The UL value of EFSA in µg kg^{-1} body weight (b.w.) per day is multiplied by the average body weight of a Vietnamese adult of 58 kg for males and 45 kg for females and listed in Table 3. The intake of Pb, U, Sb, and Sn by eating rice are at least 10 times lower than the ULs.

For arsenic, the daily provisional tolerable intake dose of 2.14 µg As kg^{-1} b.w. issued by the Joint FAO/WHO Expert Committee on Food Additives (1989; cited in EFSA 2009b) is used in this analysis. It corresponds to a daily UL of 0.096 mg As for females and 0.124 mg for males. 21 % of the samples exceed these tolerable upper intake values. The daily provisional tolerable intake dose of 2.14 µg As kg^{-1} b.w. was superseded by EFSA (2009b), which suggests a situation-oriented flexible range that is between 0.3 and 8 µg As kg^{-1} b.w. per day. This corresponds to a maximum daily uptake of 0.014 - 0.36 mg As for females and 0.017 - 0.46 mg for males. In our study, the daily As intake from only rice ranges between 0.04 and 0.12 for women and 0.05 and 0.15 for men. All calculated daily As intakes are within the range recommended by EFSA. However, all values are higher than the lower limit of 0.01 mg.

For cadmium, EFSA (2009b) proposed a daily UL of 0.36 µg kg^{-1} b.w., which corresponds to ULs of 0.016 and 0.021 mg day^{-1} for a Vietnamese female and male respectively. 46 % of the rice samples exceed this limit, and the most contaminated rice sample (HN10) is higher by a factor of 21.

Another approach for the health relevance of the rice grain data is to compare them with the permissible maximum concentration (MC) of 0.2 mg kg^{-1} for each Cd, Pb, and inorganic As in rice grains, as proposed by FAO/WHO (2014) and European Union (2006). For young children, the inorganic As concentration should be below 0.1 mg kg^{-1}. According to Suriyagoda et al. (2018), the inorganic As fraction in rice grains is 54 % of total As. Thus the resulting permissible level of total As should be 0.37 mg kg^{-1} for adults and 0.19 mg kg^{-1} for children. All samples are within the permissible As level for adults, but 54 % of the samples exceed the level for children. Rahman and Hasegawa (2011) proposed a fraction of 80 to 91 % of inorganic As in rice, which correspond to total permissible levels of 0.22 to 0.25 mg kg^{-1} for adults and 0.11 to 0.13 mg kg^{-1} for children. According to that study, 50 % of the grains surpass the As level of 0.22 mg kg^{-1} for adults, but all grain samples exceed the level of 0.11 mg kg^{-1} for children.

Twelve percent of the rice samples exceed the MC of Cd of 0.2 mg kg^{-1} as proposed by the European Union (2006). However, only 4 % of the samples would surpass the MC of Cd of 0.4 mg kg^{-1}, which has been recommended recently by the FAO/WHO (2014). Rice sample HN10 contains 0.99 mg Cd kg^{-1} that is approximately 5 times and 2.5 times higher than the limits proposed by guidelines of the European Union and the FAO/WHO respectively. The rice harvested in this area may cause a risk for human health. Fortunately, all studied samples contain Pb concentrations that is below the detection limit of 0.02 mg kg^{-1}, which is at least 10 times lower than the allowable threshold of 0.2 mg kg^{-1} as proposed by both organizations.

With the amount of daily consumed rice of Vietnamese people, the MCs of 0.2 mg kg^{-1} for Cd, Pb, and inorganic As in rice correspond to the daily maximum intake level from rice of 0.070 mg for women and 0.089 mg for men for each element. These calculated values are nearly identical with the UL values of Pb, but about 40 % lower than the UL (Table 3.3). The calculated value for Cd is, however, 4.3 times higher than its UL value for total food and drinking water as proposed by EFSA (Table 3.3). Therefore, countries with rice as the main staple food should adjust the maximum Cd concentration of 0.2 mg kg^{-1} in rice to a considerably lower level for their respective population, for example from 0.2 mg kg^{-1} to 0.05 mg kg^{-1} or lower.

3.4 Conclusion

The parent material of the paddy soils that were collected along Huong River in central Vietnam are alluvial sediments delivered from the Annam Cordillera. The alluvial sediments along the Red River consist of eroded materials from the Yunnan Plateau in China and surrounding highlands. Compared to average shale or outer Earth crust, most of the soil samples are not or only slightly polluted by toxic elements from anthropogenic activities. The concentrations of most of the potentially harmful elements are positively correlated with the concentrations of Al (an indicator of clay minerals) and Fe (Fe oxides/hydroxides), which bind most elements by sorption or co-precipitation processes. Strong positive interrelations exist within the following groups: Co, Cr, and Ni; As, Bi, Cu, and Pb; Cd, Zn, and Sb.

80% of the soil samples exceed the permissible As limit for Vietnamese agricultural soils. Elevated As and Bi concentrations presumably stem from natural sources and are regulated by redox mechanisms. In an area 60 km northwest of Hanoi, one site is polluted by numerous potentially toxic elements and two other sites are contaminated by Cr and Fe. Pollution sources may be wastewater from a local fertilizer and chemical factory. Also, two paddy soils located 120 km northwest of Hanoi, that are directly flooded by the Red River, contain elevated contents of As, Bi, Cd, Ce, Cu, La, Mn, Pb, Sb, and Sn, probably caused by upstream mining activities.

The element transfer from soil into rice grains depends on soil factors such as pH, Eh, organic matter, Fe-, Mn-, and Al-oxides/hydroxides, and clay minerals. The transfer factors decrease in the following order: P, S > Mo, Zn, Mg, K, Cd > Rb, Cu, Mn, Ca, Sn, As > Ni, Sr, Cs, Ba, Nb, Co > Cr, Na, Bi, Tl, Fe, Pb, Sb, Sc, Zr, Hf, U, La, Ce, Li, Al, Ti, Th. Some element groups show a slight positive trend of the transfer factors: As, Sb, and U; Co, Cu, Ni, and Zn; Cd and Mn.

With reference to the recommended dietary allowance (RDA), the daily intake by rice consumption is very low for Ca and Fe and moderate for Zn and Cu. The average intake of Mn, Mo, P, and Cu is higher than the corresponding RDA-values but lower than the tolerable upper intake levels (UL). The Mg intake by rice consumption is even higher than the UL. The intake of most potentially harmful elements such as Co, Cu, Mo, Ni, Pb, Sb, and U is lower than their ULs. The daily intake of As is within the range of lower and upper UL, but all samples exceed the lower UL. 46% of the rice samples induce a Cd intake higher than UL. Regarding the permissible maximum concentrations of harmful elements in rice published by the FAO/WHO (2014) and the European Union (2006), Pb concentrations in all rice samples are far below the limit, whereas Cd surpasses the limit in 12% of the samples and As exceeds the limit for young children in 54%.

Further research activities should focus on the following issues:

- Improvement in the knowledge base, especially for rice grown in areas with anthropogenic contamination and in regions with high As concentrations in irrigation water and soil.
- Careful revision and harmonization of the tolerable upper intake level for As and the maximum concentrations limits for As and Cd in rice to prevent contradictory results (Sauve´ 2014). Future studies should focus on As speciation, as well as on As and Cd intake and their health risks.
- Intensification of research on how to decrease the transfer of harmful elements from contaminated soils into the rice plant. For example, to prevent As transfer from As-rich soils into rice grains, Suriyagoda et al. (2018) proposed the cultivation of rice under aerobic, intermittent flooding or alternate wetting or drying conditions. Under such conditions, Fe-oxides/hydroxides precipitate and bind As. Thus, the availability of As plant is lowered. In addition, the presence of Fe-oxides/hydroxides increases the sorption of other critical elements. To reduce the enrichment of Cd and As in grains that are grown in acidic soils, soil pH should be increased to 6.5 in order to improve sorption, and to diminish the uptake of these elements.

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3.6 Supplementary material

Supplementary material of this paper can be found in Appendix A1

3.7 References

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Chapter 4

Paddy soil geochemistry, uptake of trace elements by rice grains (Oryza sativa), and resulting in health risks in the Mekong River Delta, Vietnam

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Abstract

Soil geochemistry and phytoavailable trace elements were investigated in 80 paddy soil samples and corresponding rice grains from the Mekong River Delta in Vietnam. Soil parameters like Fe-, Al-, and Mn-phases, organic matter, and pH-value determine element concentrations in soil and affect their transfer into rice grains. Arsenic exceeded the allowed limit for Vietnamese agricultural soils in 11% of the samples, presumably caused by natural processes. Lead surpassed the limit in one soil sample. Other toxic elements were close to their natural concentrations and far below allowable limits for agricultural soil. There was no clear correlation of trace element concentrations in soils with those in corresponding grains, even if the different soil parameters and the large pH-range between 3.7 and 6.8 were considered.

To assess health risks of critical elements in rice, the thresholds of Tolerable Upper Intake Level for total food and drinking water (UL) and of Permissible Maximum Concentration (MC) for rice grains were evaluated. Surprisingly, rice grains grown on non- or low-polluted soils can surpass the upper limits. According to the UL concept, 12% of the grains exceeded the UL of As, 29% that of Cd, and 27% that of Pb for each gender. According to the MC concept, 5% of the rice grains exceeded the MC of inorganic As for adults and 38% that for young children. 24% of the grains surpassed the MC of Pb, while Cd in all grains was below the MC. The differing results of the UL and MC approaches show an urgent need for revision and harmonization concerning As, Cd, and Pb limits especially regarding countries with high rice consumption.

Keywords • nutrient and toxic elements • paddy soils • rice grains • transfer factors • Mekong River Delta • health assessments

4.1 Introduction

Soil geochemistry provides valuable hints to explain the provenance of trace elements and their enrichment in soils. Natural concentrations and anthropogenic additions determine element concentrations and toxicity in living systems (Singh et al. 2017). Anthropogenic harmful element inputs to soils may come from the atmosphere, application of sewage sludge or industrial and mining waste water as a source for Cd, Cu, Hg, Ni, Pb, and Zn (Barakat 2011; Kim et al. 2015; Akpor et al. 2014), phosphate fertilizers for Cd, U, As, Sb, and Bi (Alloway 2013; Stroebel 2008) and biocides for Cu (in earlier times also for Hg, Sn, and Pb; Gimeno-Garcia et al. 1996).

On the other hand, natural processes can also lead to unusually high concentrations of some elements. For example, naturally elevated concentrations of As and Se in sediments or soils can be caused by co-precipitation with sulfidic compounds under anaerobic conditions or by their fixation on Fe-oxides/hydroxides in oxidizing environments (Wenzel 2013; Christophersen et al. 2013; Wang et al. 2012). In the Himalayan mountains sulfidic minerals in some sediments release As during rock weathering, leading to As enrichments in soils, sediment and groundwater in Bangladesh (Hossain 2006; Meharg and Rahman 2003).

Element speciation, fixation, mobility in soils are determined by different soil parameters such as pH-Eh, the concentrations of ligands in the interstitial solution, by the concentration of organic material, Al-, Fe-, and Mn-oxides/hydroxides, and clay minerals in the soil. These conditions influence the bioavailability of elements in soil and their uptake by plants (Alloway 2013; Kabata-Pendias 2011).

From the health point of view, As and Cd are regarded as the two most important risk elements for rice-consuming people (Bolan et al. 2013; Chaney et al. 2016). Especially, adult people in eastern and southern Asia consume large amounts of rice varying between 200 and 600 g per day (Suriyagoda et al. 2018). Roychowdhury (2008), for example calculated for the adult population of Bengal Delta in India an average inorganic As exposure of 2.3 µg As kg^{-1} body weight (b.w.) day^{-1} by eating rice. This exceeds the WHO recommended maximum level of 2.1 µg As kg^{-1} b.w. day^{-1}. Additional As-sources such as drinking water or eating other foods are not included in that study, but would increase the As-intake. In Bangladesh, Hossain (2006) estimated, that more than 25 million people are facing potential As poisoning from water and rice consumption, whereas Rahman et al. (2018) projected that even 35 – 77 million people are health-affected just by water consumption. Sauvé (2014) described the existing arsenic guidelines as a cost-benefit compromise and, as such, they should be periodically re-evaluated in favor of health aspects. Consequences of As exposure are skin lesions, cancer of lung, liver, and bladder (EFSA 2009a; Lin et al. 2013; Smith et al. 2006; Tchounwou et al. 2019).

In the 1960s for the first time, the world witnessed severe Cd poisoning by rice consumption that caused the Itai-Itai disease in Toyama Prefecture, Japan. Nogawa et al. (2017) calculated from Cd concentrations of thousands of rice samples in this area a threshold limit concentration of 0.27 mg kg^{-1} to prevent the Itai-Itai disease. For Chinese population, rice is the most important Cd-source compared to other food (Yu et al. 2017). Chronic Cd exposure can cause renal dysfunction, bone demineralization, as well as cancer of lung, endometrium, bladder, and breast (EFSA 2009b).

In addition to As and Cd, the toxic element Pb can also be enriched in rice grains (Norton et al. 2014; Shraim 2017). Chronic Pb-exposure causes developmental neurotoxicity in young children, cardiovascular effects and nephrotoxicity in adults and many effects such as headaches, convulsions, tremors, paralysis, and probable cancer (EFSA 2010).

Vietnam is one of the main rice producing and consuming countries. The Mekong River Delta – the largest granary in Vietnam – produces more than 50% of total national rice (Thuy and Anh 2015). The paddy soils in this delta consist of fertile alluvial material in combination with plentiful water. The Mekong River provides about 160 million tons suspended sediment in 475 000 million cubic meters' water per year (Hung 2011). The Mekong River originates in the Tibetan plateau (China) and flows through Burma, Thailand, Laos, Cambodia and finally Vietnam where it disembogues into the South China Sea. Inhabitants of Laos, Cambodia, and Vietnam living along the Mekong River are facing a chronic As exposure consuming naturally As-enriched groundwater and crops grown on soils contaminated by irrigation (Buschmann et al. 2008; Chanpiwat et al. 2011; Huang et al. 2016). More than 17 million people live in the Mekong River Delta area in Vietnam. Most of their income is based on rice cultivation (Huang et al. 2016).

Soil geochemistry combined with data of rice composition are a key to understand the transport of nutrient and harmful elements into the rice grains and resulting health aspects. The main research aims of our study are: (1) distinction of natural and anthropogenic element concentrations in paddy soils in the Mekong River Delta; (2) influence of soil parameters regarding retention and phytoavailability of elements for rice grains; (3) aspects of rice composition and health risks for people.

4.2 Material and methods

4.2.1 Sampling, sample preparation, analysis, and quality control

Soils and corresponding rice grains were collected in April 2017 within a 10-day period before rice harvesting at 80 sites in the Mekong River Delta area of Vietnam. The soil samples were taken in the root zone of the rice plants at depths between 0 to 10 cm.

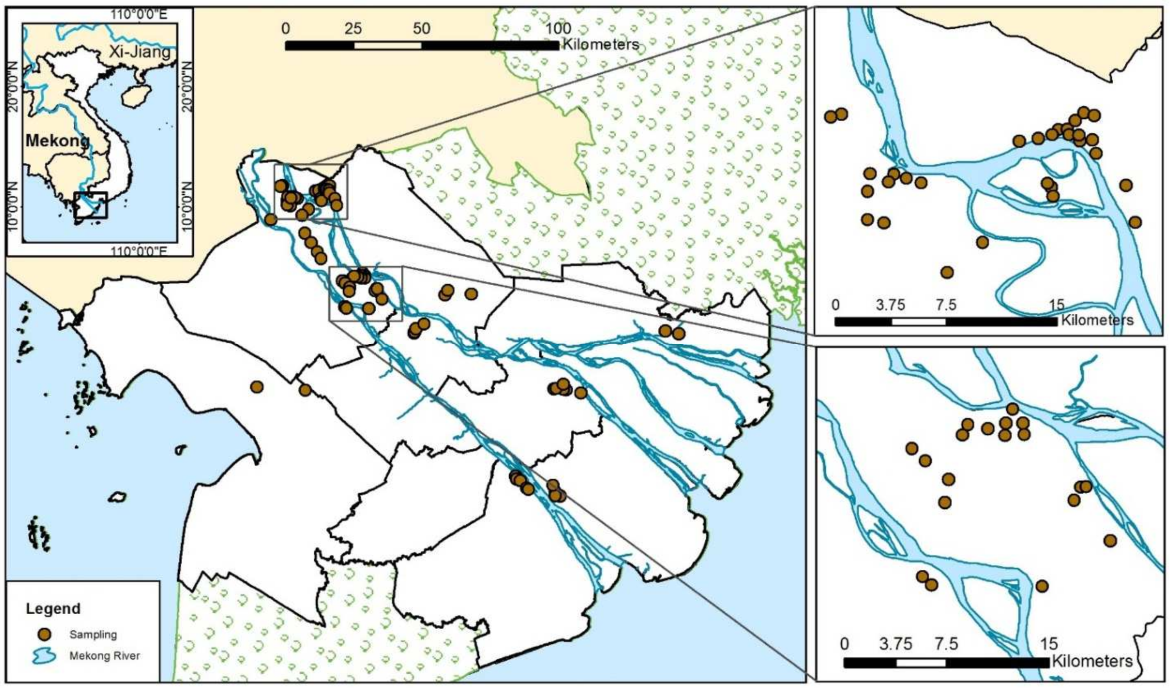

Fig. 4.1 Map of sample locations in the Mekong River Delta area, Vietnam

Before analysis, the soil samples were dried at 105 ^{0}C, rice grains at 60 ^{0}C, then grounded to a particle size <63 µm by a Fritsch© agate ball mill for soils and by an agate hand mortar for the rice grains. The pH-values of air-dried soils were measured in a 0.01 M $CaCl_2$ solution (1:2.5) using the glass electrode ProfiLine pH/mV-Meter 197. To quantify the total concentration of elements in soil and rice grains, the milled samples were completely digested in a closed ultra-clean PTFE vessel (PicoTrace®, Bovenden, Acid Sample Digestion System DAS 30): about 700 mg of dried milled rice were digested by 4 ml HNO_3, 0.5 ml HF, and 3 ml $HClO_4$, about 150 mg of dried milled soils by 2 ml HNO_3, 3 ml HF, and 3 ml $HClO_4$. The reason for the use of HF to digest the rice grains was to identify if adhering soil or dust material contaminated the samples or if all the elements were taken up by physiological processes. The digestion solutions were measured afterwards by two analytical tools: ICP-OES (Inductively Coupled Plasma - Optical Emission Spectrometry) 5100 VDV (Agilent) and ICP-MS (Inductively Coupled Plasma - Mass Spectrometry) Thermo Scientific iCAP Q (Thermo Fisher

Scientific). Loss on ignition (LOI) was determined by weight loss after heating the dried soil samples to 530 °C for 24 hours. The concentration of SiO_2 was calculated by the following equation:

$$SiO_2 = [100 – (\text{main element oxides} + \text{minor element oxides} + \text{LOI})] \qquad (\text{wt. \%})$$

To ensure the accuracy and precision of the element data, the following reference materials were measured (see the compilation of the results in the supplement of the previous paper of Nguyen et al. 2019): GSJ-JA-2 (Andesite), GSJ-JLK-1 (Lake Sediment), NCS-DC-73349 (Branches and Leaves of Bush), WEPAL-IPE 126 (Maize plant), and WEPAL-IPE-168 (Sunflower). Deviations from the element concentrations of certified reference materials were smaller than 10% for most elements, but Bi, Mo, and Zr showed deviations of up to 20%.

4.2.2 Data and statistical analysis

The software IBM statistics 20 was used to calculate how trace element concentrations depend on soil parameters by using the module Multiple Linear Regression Analysis. The relations between trace element concentration y and soil parameters x_n are modeled according to the regression equation:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon$$

where β_0 is a constant (intercept), β_n are slopes (regression coefficients), and ε is the standard error of the estimate.

For each element, soil parameters were selected according to significance levels below 0.05 for the regression coefficient, coefficient of determination R^2, and standard error ε.

To describe the transport of elements from soils into rice grains, transfer factors (*TF*) were calculated as ratio of element concentration in grain (El_{grain}) to that in corresponding soil (El_{soil}):

$$TF = El_{grain} / El_{soil}$$

4.3 Results and discussion

4.3.1 Soil geochemistry

Parent materials of paddy soils within the Mekong River Delta area in Vietnam are composed of alluvial delta sediments delivered from the Tibetan Plateau and lower mountains along the river course. The geochemical data for each soil sample are compiled in Tables S1 and S2 of the supplementary material. The paddy fields contain on average 10.3% LOI (Table 4.1), a representative for organic material (OM) and water in mineral structures like Al-, Fe-, and Mn-oxides/hydroxides and clay minerals. The pH-values of the delta soils range from 3.7 to 6.8 with 50% of the samples between 3.7 and 4.9, 34% between 5.0 and 5.5, and 16% between 5.5 and 6.8. Acidification of paddy soils can be due to organic acidic groups and/or the application of ammonium nitrate fertilizers.

Table 4.1 Statistics of main and trace element concentrations in soils of the Mekong River Delta (n = 80). For comparison, mean values for soils along the Red River (n = 24) in northern Vietnam and Huong River (n = 5) in central Vietnam, average shale and Earth's crust data as well as allowable limits for agricultural soils are listed.

Element	Unit	Mekong River							Huong River	Red River	Shale	Earth's crust	Allowable limit
		Min	Q1	Median	Q3	Max	Mean	Stdev					
pH	-	3.7	4.6	4.9	5.3	6.8	5.0	0.6	4.4	6.2	-	-	-
LOI	%	4.7	8.6	10.2	11.9	18.8	10.3	2.6	6.4	6.5	-	-	-
Al_2O_3	%	11.9	14.8	16.5	18.4	20.9	16.5	2.2	14.1	14.3	15.1[a]	15.4[c]	-
CaO	%	0.30	0.44	0.49	0.55	1.27	0.52	0.14	0.31	0.80	3.3[b]	3.6[c]	-
Fe_2O_3	%	2.63	4.57	5.14	5.44	6.78	4.97	0.83	4.94	6.32	6.9[d]	5.0[c]	-
K_2O	%	1.89	2.19	2.35	2.55	2.78	2.37	0.22	2.38	2.42	3.8[b]	2.8[c]	-
MgO	%	0.70	0.99	1.08	1.17	1.33	1.07	0.15	0.96	1.35	2.7[d]	2.5[c]	-
MnO	%	0.009	0.024	0.033	0.046	0.161	0.039	0.024	0.033	0.068	0.11[d]	0.10[c]	-
Na_2O	%	0.40	0.56	0.61	0.69	0.86	0.62	0.10	0.40	0.71	1.0[b]	3.3[c]	-
P_2O_5	%	0.09	0.13	0.17	0.20	0.32	0.18	0.05	0.11	0.20	0.16[a]	0.15[c]	-
S	%	0.015	0.047	0.072	0.113	0.431	0.093	0.072	0.052	0.065	0.24[a]	0.056[c]	-
TiO_2	%	0.64	0.76	0.79	0.84	1.01	0.80	0.06	0.81	0.81	0.77[d]	0.64[c]	-
SiO_2	%	54	60	62	66	72	63	4.3	70	67	61[b]	67[c]	-
As	$mg\ kg^{-1}$	8.3	10.9	12.4	13.7	28.9	12.6	3.2	13.6	22.5	10.0[d]	4.8[c]	15[e]
Ba	$mg\ kg^{-1}$	283	373	399	420	487	394	42	460	417	636[b]	624[c]	-
Bi	$mg\ kg^{-1}$	0.29	0.37	0.40	0.43	0.52	0.40	0.05	0.56	0.88	0.13[d]	0.16[c]	-
Cd	$mg\ kg^{-1}$	0.16	0.22	0.29	0.32	0.43	0.27	0.06	0.25	0.37	0.13[d]	0.09[c]	1.5[f]
Ce	$mg\ kg^{-1}$	68	76	81	85	108	81	7	83	90	67[b]	63[c]	-
Co	$mg\ kg^{-1}$	5.6	11.8	13.7	14.9	20.6	13.2	3.0	13.3	15.7	19.0[d]	17.3[c]	20-50[e]
Cs	$mg\ kg^{-1}$	7.2	9.6	11.1	12.8	15.1	11.2	2.0	6.3	8.1	5.2	4.9[c]	-
Cu	$mg\ kg^{-1}$	20.1	27.3	29.2	33.2	43.0	30.0	4.2	27.1	47.8	45[d]	28[c]	100[f]
Hf	$mg\ kg^{-1}$	3.1	3.9	4.1	4.4	5.3	4.1	0.4	3.8	4.1	6.3[b]	5.3[c]	-
La	$mg\ kg^{-1}$	34	38	40	43	53	41	4	41	44	31[b]	31[c]	-
Li	$mg\ kg^{-1}$	35	43	50	58	76	50	9	27	40	66[a]	21[c]	-
Mo	$mg\ kg^{-1}$	0.49	0.68	0.86	1.07	2.63	0.94	0.36	1.07	0.98	1.3[d]	1.1[c]	4-10[e]
Ni	$mg\ kg^{-1}$	23.2	31.8	36.3	39.2	50.4	36.3	5.8	28.5	39.9	68[d]	47[c]	20-60[e]
Pb	$mg\ kg^{-1}$	20.9	24.9	26.6	28.6	190	28.6	18.5	29.7	50.5	22[d]	17[c]	70[f]
Rb	$mg\ kg^{-1}$	94	111	121	134	154	123	15	117	119	125[b]	84[c]	-
Sb	$mg\ kg^{-1}$	1.07	1.82	2.02	2.28	6.45	2.06	0.62	1.58	2.01	2.1[b]	0.4[c]	10[e]
Sn	$mg\ kg^{-1}$	3.22	3.92	4.22	4.39	5.18	4.15	0.38	4.56	4.81	2.5[d]	2.1[c]	50[e]
Sr	$mg\ kg^{-1}$	71	80	83	87	108	84	6	41	82	142[b]	320[c]	-
Th	$mg\ kg^{-1}$	12.6	14.7	15.4	16.1	17.5	15.3	1.0	19.2	17.5	12.3[b]	10.5[c]	-
Tl	$mg\ kg^{-1}$	0.50	0.60	0.67	0.72	0.83	0.66	0.08	0.59	0.60	0.68[d]	0.90[c]	-
U	$mg\ kg^{-1}$	3.59	4.18	4.41	4.71	5.66	4.45	0.41	4.53	3.74	2.7[b]	2.7[c]	-
V	$mg\ kg^{-1}$	84	100	114	120	139	111	13	97	111	130[d]	97[c]	-
Zn	$mg\ kg^{-1}$	51	78	90	100	134	90	16	83	110	95[a]	67[c]	200[f]
Zr	$mg\ kg^{-1}$	115	145	152	163	197	154	15	110	129	160[a]	193[c]	-

[a] Turekian and Wedepohl (1961); [b] Gromet et al. (1984); [c] Rudnick and Gao (2003); [d] Wedepohl (2004); [e] Kabata-Pendias (2011); [f] QCVN (2015): Vietnamese guideline for agricultural soil; Red River and Huong River soils data from Nguyen et al. (2019)

The average concentrations of main and trace elements in the studied soils from the Mekong area were compared to the mean global shale composition (Table 4.1) to point out the depletion or enrichment of elements. The reason for using average shale as background composition is due to the lack of soil data. The ratio of average element concentrations in Mekong soils to those in shale increases as follows:

- Depleted elements (ratio from 0.15 to 0.9): Ca, Mn, S, Mg, Ni, Sr, Na, Ba, K, Hf, Cu, Co, Mo, Fe, Li, V
- Elements with little changes (0.9 to 1.1): Zn, Zr, Tl, Rb, Sb, Si, Ti, Al
- Enriched elements (1.1 to 3.1): P, Ce, Th, As, Pb, La, U, Sn, Cd, Cs, Bi.

The depletion of alkaline, earth-alkaline elements, and S may be explained by the delivery of soil material from pre-weathered landscapes. Furthermore, the decrease of these elements can be additionally promoted by low pH-values in the soil. The dissolution of Fe- and Mn-oxides/hydroxides under reducing conditions or at low pH-values (84% of the soils have pH <5.5) may diminish their soil concentrations. The elements Zr, Tl, Rb, Si, Ti, and Al are resistant to weathering and keep ratios around 1. The application of phosphate fertilizer originating from apatite not only increased phosphorus, but also concomitant elements such as Cd and U in the paddy soils (Chen and Graedel 2015). The soil As- and Bi-enrichment is suggested to be due to natural redox and co-precipitation processes related to Fe-oxides/hydroxides. In contrast, the Pb-enrichments in soils may be caused by anthropogenic emissions from transportation (former Pb-containing gasoline), non-ferrous metal industry and energy production (especially coal), and the sedimentation of contaminated suspended riverine materials.

The element concentrations in Mekong Delta soils were compared with those of the Red River in north and the Huong River in central Vietnam (Nguyen et al. 2019; Table 4.1). Most elements showed similar enrichments or depletions within the three areas. This can be explained by a similar provenance and weathering stage of the suspension in the rivers. However, the concentrations of easily dissolvable elements Ca, Mn, Mg, Na, Zn, P and Fe in Red River were slightly higher than those in the Mekong and Huong River. This is consistent with higher pH-values in the Red River soils (mean pH = 6.2) than in the Mekong River soils (mean pH = 5) and Red River soils (mean pH = 4.4). In addition, the considerably higher concentrations of As and Bi in Red River soils may partially result from higher content of Fe-oxides/hydroxides, the most important sorbents of As and Bi. The enrichment of Cd and Pb in

Red River soils can be caused by anthropogenic influences such as phosphate fertilizer application and emissions from energy production or industrial activities.

Except for As and Pb, the other critical elements were within the permissible soil levels from the Vietnamese Ministry of Natural Resource and Environment (QCVN 2015) and from other countries. 11% of Mekong Delta soils exceed the As-threshold of 15 mg kg^{-1}. The increased As-concentrations were probably a consequence of the aforementioned natural causes, even for the samples MK8 and MK9 with 29 and 25 mg As kg^{-1} respectively. Consistent with soils, Luu (2019) mentioned that 26% of groundwater samples from the Mekong River Delta As-values were higher than the limit of 10 µg L^{-1}.

Soil sample MK14 shows extreme concentrations of 190 mg kg^{-1} Pb and 6.4 mg kg^{-1} Sb, corresponding to 7- and 3-times enrichments respectively compared to their mean contents. This site is 200 meters away from a small husking rice factory. Previous use of leaded gasoline may be a source for Pb and tire abrasion for Sb.

Two highly correlated element groups could be distinguished (Fig. 4.2):

- Highly significant correlations existed between the elements K, Al, Li, Rb, Cs, Tl, V, and Ba. These elements are bound in K-rich alumino-silicate minerals such as K-feldspars, illite/muscovite and clay minerals. The alkaline elements Li, Rb, Cs, as well as Tl and Ba can substitute K; V may replace Al in clay mineral structure. A significant positive correlation between K, Fe, and Mg suggests the existence of biotite. The highly significant negative correlations of Si with LOI (a proxy for OM and water), Al, K, Li, Rb, Cs, Tl, V, and Ba could be attributed to the dilution by quartz (nearly pure SiO_2) or opal (SiO_2 with some water). It must be considered that this dilution causes spurious positive correlations within this element group. The correlation of LOI with Al, K, Li, Rb, Cs, Tl, V, and Ba may be due to presence of water in clay minerals. The enrichment of S in organic material leaded to a positive correlation of S with LOI. The low Fe-concentration in some S-rich samples suggest that some of the S may exist in elementary form and not as Fe-sulfide. This was evident in sample MK82 containing 0.43% S and only 2.2% Fe. The increase of Mn-concentration with rising pH may be caused by the oxidation of Mn^{2+} ion and formation Mn^{IV}-oxides/hydroxides. In addition, the negative correlation of Mn with LOI may indicate less reducing soil environments and less microbial reduction and dissolution of already existing Mn^{IV}-phases at higher LOI-contents. The negative correlation of LOI and pH may be caused by a better preservation of OM in acidic soils due to lower activities of oxidizing organisms. In addition, weak acidic groups in OM may decrease the pH of paddy soils. The low pH-values facilitated the dissolution of Mn- and Fe-oxides/hydroxides (Chen et al. 2003).

- The extremely strong correlation between Hf and Zr (r = 0.99) was caused by their usually constant ratio in parent materials and their poor mobility in soil. They are often bound in own, weathering-resistant phases like Zr.

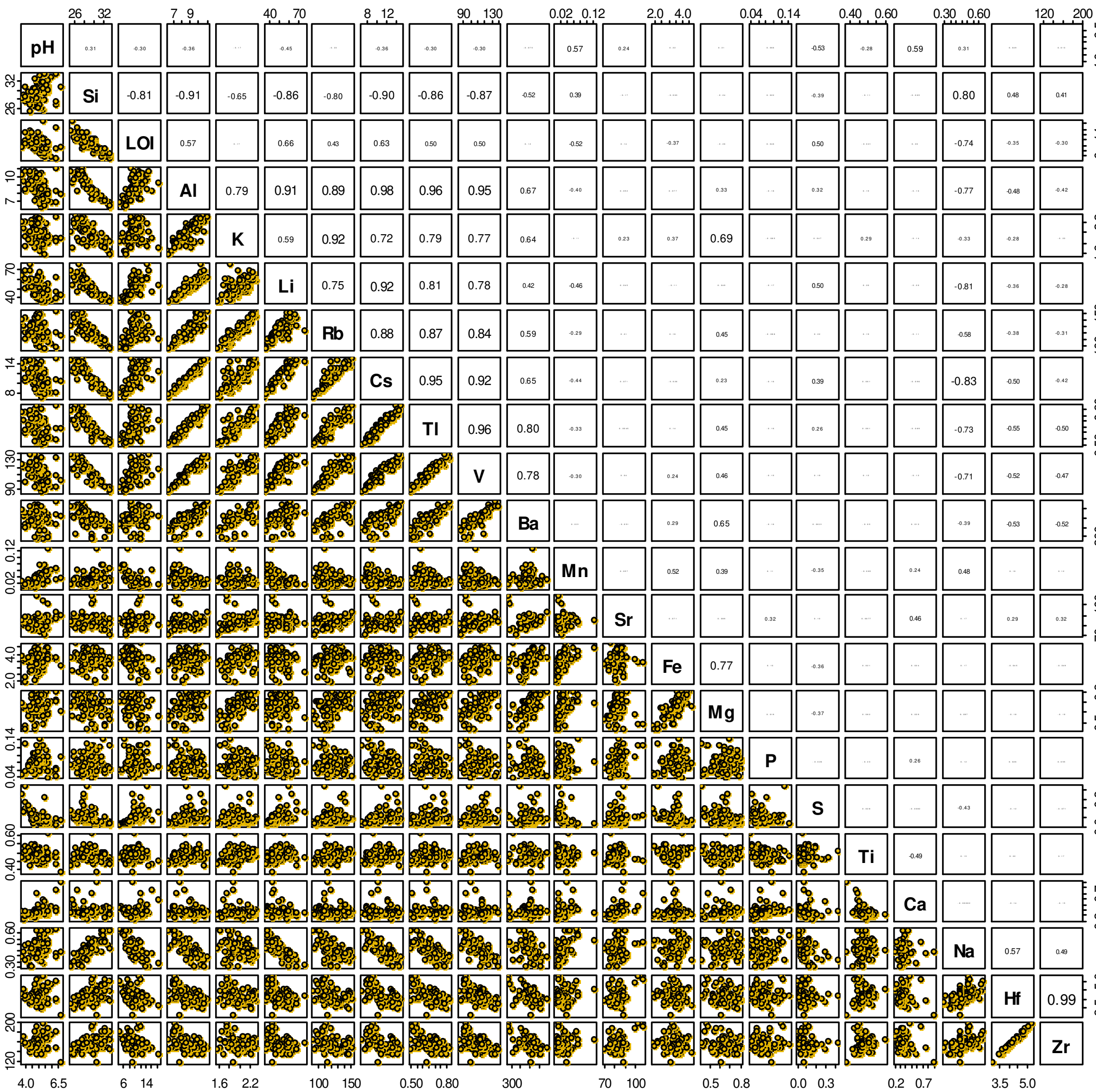

Fig. 4.2 Scattergram and correlation matrix of concentrations of selected main and trace elements, pH, and LOI in soils of the Mekong River area (main and minor elements in wt. %; trace elements Li, Sr, Rb, Cs, Tl, V, Ba, Hf and Zr in mg kg^{-1})

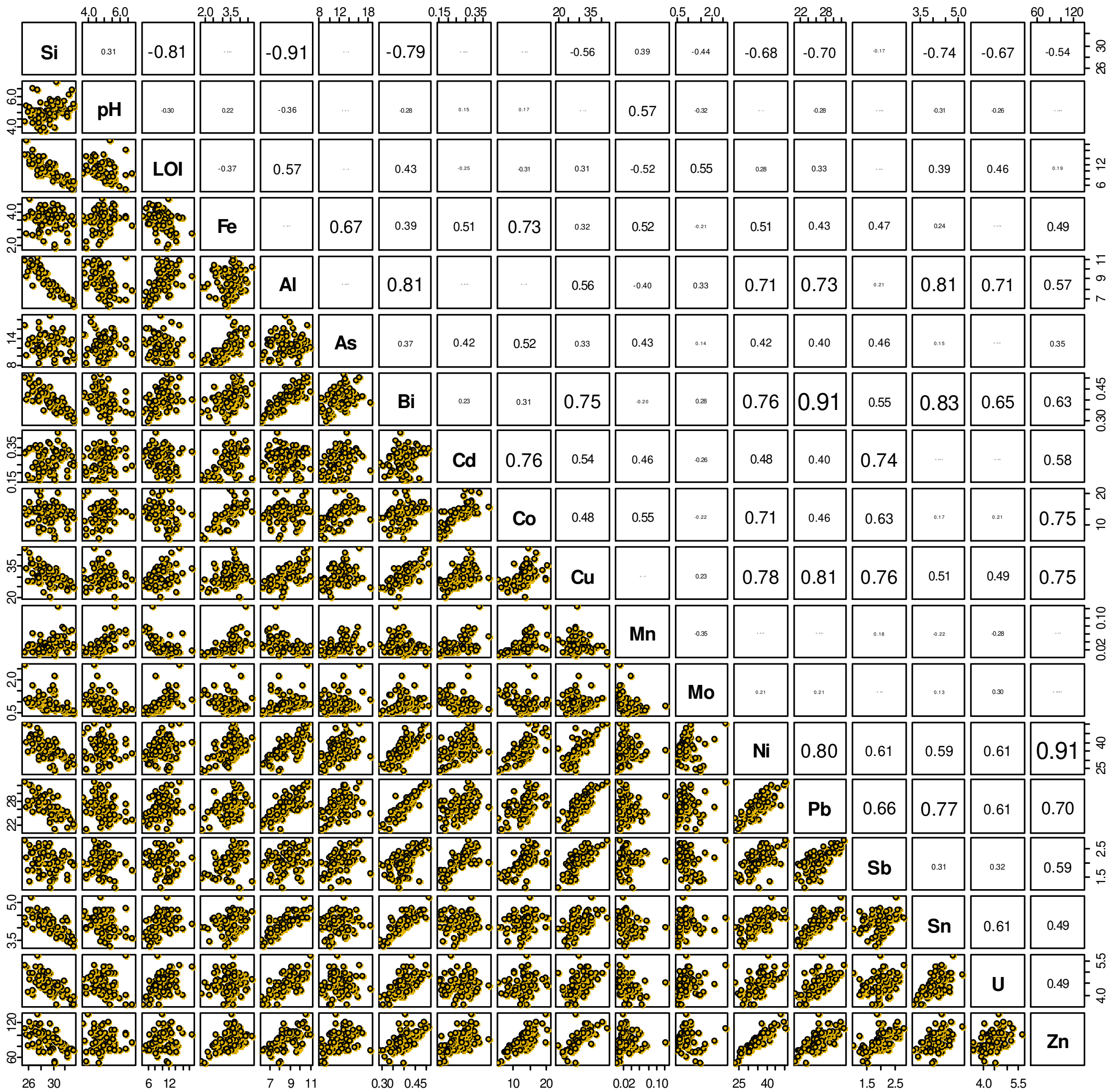

Fig. 4.3 Scattergram and correlation matrix for pH, LOI, selected main elements (in wt. %), and critical trace elements (mg kg^{-1}) in soils of the Mekong River Delta. Pb (190 mg kg^{-1}) and Sb (6.5 mg kg^{-1}) in sample MK-14 as well as As in MK-8 (29 mg kg^{-1}) and MK-9 (25 mg kg^{-1}) are excluded

In addition to parent materials, element concentrations in soils are impacted by soil factors like pH, concentration of OM, Al-, Fe-, Mn-oxides/hydroxides, and clay minerals. These factors play an important role for holding and fixing trace elements in soils and determine their phytoavailability. Oxides/hydroxides, clay minerals and OM act as sorbents binding toxic element ions on their surfaces (Alloway 2013; Kabata-Pendias 2011). Organic material may additionally form soluble complexes with some metals such as Cu, Pb, and Mo

(Greger 2004) or provide electrons for the reduction of Fe- and Mn-oxides/hydroxides and of the oxyanions arsenate, bismutate, molybdate, vanadate, and antimonate. The effect of pH on release or retention of trace elements in soils has two facets: (1) low soil-pH directly increases the solubility of sorbed trace metal cations thereby increasing their mobility but lowering the mobility of anions; (2) low soil-pH increases the solubility of Fe- and Mn-oxide/hydroxides releasing sorbed metal ions. In contrast, higher pH-values lead to increased sorption of trace element cations and/or co-precipitation with oxides/hydroxides. However, correlations between trace element concentrations and the pH-values in Mekong soils were not significant, except for Mn (Fig. 4.3). Trace element concentrations exhibit positive correlations with Al- and Fe-oxide/hydroxide and OM. The increase of concentrations of As, Cd, Co, and Sb can be partially explained by increasing concentrations of Fe-phases, that of Bi, Cu, Mo, Ni, Pb, Sn, Tl, U, V, and Zn by rising concentrations of Al-phases (Fig. 4.3). In addition, the positive correlation between Al- and LOI-concentrations induced positive association of the Al-correlated elements with LOI as well. Molybdenum had a strong positive correlation with LOI caused by the strong sorption of molybdate anions on humic acids in reducing soils (Kabata-Pendias 2011).

The application of multiple regression analysis can give a more reliable estimate for the influence of the main soil components on the trace element concentrations. As master variables, five soil parameters pH, LOI (as a proxy for OM), Fe, Al, and Mn (as representatives for oxides/hydroxides and clay minerals) were chosen. Table 2 shows multiple regression equations describing the dependency of the trace element concentration on main soil parameters at significance levels of ≤ 0.05, coefficient of determination R^2 at maximum and the standard error of estimate ε at minimum. These equations were partially suitable to give a calculation and estimate of trace element concentrations in uncontaminated paddy soils of the Mekong Delta. Scattergrams of measured content versus modeled content for selected trace elements are presented in Fig. A2.1 (Appendix A2).

Table 4.2 Regression models to estimate some trace element concentrations (mg kg^{-1}) in soils in the Mekong River Delta based on soil parameters (wt. %) and pH. The importance of soil factors is listed in decreasing order.

Regression equation	Std. Error of Estimate (ε)	R^2	Importance of soil factors
[As] = 5.98 – 1.04[pH] + 0.199[LOI] + 2.22[Fe] +58.9 [Mn]	1.47	0.55	Fe, Mn, pH
[Bi] = 0.021 + 0.004[LOI] + 0.033[Fe] + 0.026[Al]	0.02	0.78	Al, Fe, LOI
[Cd] = 0.11 + 0.04[Fe] + 0.9[Mn]	0.05	0.32	Fe, Mn
[Co] = -2.7 + 0.58[Al] + 2.62[Fe] + 58.4[Mn]	1.89	0.61	Fe, Mn, Al

[Cu] = 6.4 + 1.91[Al] + 2[Fe]	3.4	0.38	Al, Fe
[Mo] = 0.14 + 0.077[LOI]	0.3	0.30	LOI
[Ni] = -9.1 + 3.331[Al] + 4.571[Fe]	3.2	0.71	Al, Fe
[Pb] = 7.26 + 1.539[Al] + 1.688[Fe]	1.5	0.68	Al, Fe
[Sb] = 0.78 + 0.369[Fe]	0.25	0.42	Fe
[Sn] = 1.55 + 0.114[Fe] + 0.253[Al]	0.21	0.68	Al, Fe
[Tl] = 0.07 + 0.067[Al]	0.02	0.92	Al
[U] = 2.28 + 0.25[Al]	0.29	0.51	Al
[V] = 8.03 + 10.34[Al] + 3.7[Fe]	3.5	0.93	Al, Fe
[Zn] = -15 + 7.16[Al] + 12.17[Fe]	11	0.53	Al, Fe

The results of Table 4.2 confirm the main conclusions from the bivariate plots in Fig. 4.3, but clarify that usually more than one soil factor was responsible to explain the concentration of trace elements in soil. Al-phases like clay minerals determine the concentrations of Tl, V, Bi, Sn, Pb, U, Ni, Zn, and Cu (in decreasing order). Fe-phases such as oxides/hydroxides regulate the concentrations of Co, As, Cd, Sb, and to a lesser extent those of Bi, Cu, Ni, Pb, Sn, V, and Zn; organic matter the concentration of Mo. Mn-phases influence slightly the concentrations of As, Cd, and Co, pH that of As.

4.3.2 Transfer of nutrient and trace elements into rice grains

Statistical values of element concentrations in unpolished rice grains and transfer factor soil-to-grain are compiled in Table 4.3. Detailed data for grain composition in the Mekong area are compiled in Tables A2.3 and for TFs in Table A2.4 (Appendix A2). The data show a negligible transfer of Ti, Ce, La, Th, U, Zr, Hf, Al, V, Li, Tl, Sb, and Fe into rice grains. Especially the extremely low Ti concentrations indicate very low, negligible amount of adhering soil or dust material in the rice grains. Most of the concentrations of these elements were below detection limit. The insolubility of these elements in soils causes their low bioavailability and uptake. In contrast, K, Mg, P, and S from fertilizers have high bioavailability because they are much more soluble. That may explain the high correlation of P with Mg ($r = 0.92$) and K ($r = 0.75$) in the grain (Fig. A2.2 in Appendix A2). The reduction of Fe- and Mn-oxides/hydroxides in paddy soils and the release of dissolved Fe^{2+} and Mn^{2+} ions facilitated the uptake of these elements into grains. There were weak positive correlations between Ni, Co, Cd, and Cu in rice grains (Fig. A2.3 in Appendix A2), whereas As showed slight negative correlations with Cd, Cu and Ni.

Table 4.3 Element concentrations (mg kg^{-1}) in rice grains and transfer factors of the Mekong River area (n = 78) in comparison with mean values of the Huong River area in central Vietnam (n = 4) and the Red River area in northern Vietnam (n = 19) from Nguyen et al. (2019)

	Concentration in rice grains							**Transfer factor**						
Element	**Mekong River**					**Huong River**	**Red River**	**Mekong River**					**Huong River**	**Red River**
	Min	Median	Max	Mean	Stdev			Min	Median	Max	Mean	Stdev		
Al	<4	<4	19	<4	-	<4	<4	<0.00004	<0.00005	0.00019	<0.00005	-	<0.00009	<0.00007
Ca	66	86	113	87	11	139	134	0.01	0.02	0.05	0.03	0.01	0.06	0.04
Fe	6.6	10.1	17.4	10.3	1.81	13	11	0.0002	0.0003	0.0009	0.0003	0.0001	0.0004	0.0003
K	1817	2580	3462	2595	278	2945	2910	0.10	0.13	0.18	0.13	0.02	0.15	0.16
Mg	1011	1282	1562	1290	119	1240	1394	0.14	0.19	0.34	0.20	0.04	0.22	0.20
Mn	13	21	29	21	4	24	22	0.02	0.08	0.21	0.09	0.05	0.09	0.06
Na	3.3	6.1	29.1	7.6	4.7	5.5	4.2	0.0006	0.0014	0.0063	0.0017	0.0011	0.0019	0.0012
P	2469	3281	3926	3269	313	3235	3576	2.1	4.2	8.6	4.5	1.4	6.7	4.8
S	624	875	1113	880	105	1051	1098	0.2	1.2	5.3	1.4	0.9	2.6	2.9
Ti	<0.05	<0.05	0.41	<0.07	-	0.33	<0.07	<0.00001	<0.00001	0.00009	<0.00001	-	0.00007	<0.00002
As	0.08	0.16	0.56	0.18	0.09	0.27	0.13	0.006	0.013	0.044	0.015	0.008	0.020	0.009
Ba	0.05	0.43	1.59	0.51	0.33	1.51	1.24	0.0001	0.0010	0.0036	0.0013	0.0008	0.0033	0.0033
Bi	<0.0002	0.0003	0.0019	<0.0004	-	0.0017	<0.0003	<0.0005	0.0009	0.0048	<0.0011	-	0.0026	<0.0008
Cd	0.001	0.024	0.187	0.037	0.039	0.085	0.116	0.005	0.09	0.93	0.15	0.181	0.37	0.36
Ce	<0.0006	<0.0006	0.0018	<0.0007	-	0.0058	<0.0009	<0.00001	<0.00001	0.00002	<0.00001	-	0.00006	<0.00002
Co	0.008	0.022	0.115	0.025	0.017	0.083	0.017	0.001	0.002	0.011	0.002	0.002	0.007	0.002
Cs	0.002	0.02	0.15	0.03	0.02	0.43	0.04	0.0001	0.0022	0.0113	0.0026	0.0021	0.0802	0.0198
Cr	<0.1	<0.1	0.64	<0.15	-	<0.1	<0.1	-	-	-	-	-	-	-
Cu	1.1	3.1	10.2	3.3	1.4	3.6	3.3	0.03	0.10	0.40	0.11	0.05	0.14	0.09
Hf	<0.0002	<0.0002	0.0007	<0.0002	-	<0.0005	<0.0003	<0.00004	<0.00005	0.0002	<0.00005	-	<0.00005	<0.00009
La	<0.0003	<0.0003	0.0010	<0.0004	-	0.0032	<0.0005	<0.00001	<0.00001	0.00003	<0.00001	-	0.00007	<0.00002
Li	<0.006	<0.006	0.028	<0.006	-	<0.014	<0.006	<0.0001	<0.0001	0.0005	<0.0001	-	<0.0005	<0.0002
Mo	0.11	0.40	1.02	0.41	0.17	0.69	0.62	0.10	0.44	1.62	0.49	0.27	0.72	0.98
Ni	0.03	0.26	0.96	0.30	0.19	0.95	0.35	0.001	0.008	0.031	0.009	0.006	0.039	0.015
Pb	0.02	0.10	0.93	0.17	0.19	<0.02	<0.02	0.001	0.004	0.034	0.006	0.007	<0.0007	<0.0005
Rb	1.1	11.3	52.1	11.5	7.7	44	13	0.008	0.090	0.447	0.096	0.066	0.41	0.19
Sb	<0.0006	<0.0006	0.0026	<0.0007	-	<0.0006	<0.0006	<0.0001	<0.0003	0.0012	<0.0004	-	<0.0005	<0.0004
Sn	<0.06	<0.06	2.57	<0.16	-	<0.06	<0.06	<0.01	<0.01	0.76	<0.04	-	<0.014	<0.014
Sr	0.19	0.35	0.55	0.35	0.09	0.47	0.36	0.002	0.004	0.007	0.004	0.001	0.012	0.006
Th	<0.0002	<0.0002	0.0003	<0.0002	-	0.0009	<0.0002	<0.00001	<0.00001	0.00002	<0.00001	-	0.00004	<0.00002
Tl	<0.0002	<0.0002	<0.0002	<0.0002	-	<0.0003	<0.0002	<0.0002	<0.0003	<0.0004	<0.0003	-	<0.0005	<0.0004
U	<0.0001	<0.0001	0.0002	<0.0001	-	0.0006	<0.0001	<0.00002	<0.00002	0.00004	<0.00002	-	0.00013	<0.00005
V	<0.008	<0.008	0.024	<0.009	-	<0.046	<0.008	<0.00006	<0.00007	0.00027	<0.00008	-	<0.00043	<0.00014
Zn	15	19	27	20	2	27	23	0.13	0.22	0.40	0.23	0.06	0.33	0.24
Zr	<0.007	<0.007	0.027	<0.007	-	<0.02	<0.05	<0.00004	<0.00005	0.0002	<0.00005	-	<0.0002	<0.0001

The transfer factors soil-to-grain of elements (Fig. 4.4) increased in the following order:

- TF ≤ 0.001: Ti, Ce, La, Th, U, Zr, Hf, Al, V, Li, Tl, Sb, Fe
- 0.001 < TF ≤ 0.01: Cr, Bi, Ba, Na, Co, Cs, Pb, Sr, Ni, Sn
- 0.01 < TF ≤ 0.1: As, Ca, Mn, Rb, Cd
- 0.1 < TF ≤ 1: Cu, K, Mg, Zn, Mo
- 1 < TF < 5: S, P

Scattergrams in Fig. A2.4 (Appendix A2) visualize that the element concentrations in rice grains were not correlated with their total concentrations in soils. To better understand the dominant factors, that determine the soil-plant transfer in the Mekong area, ratios of maximum to minimum concentrations for selected elements in rice grains and soils as well as the ratios of TF are compiled in Table 4.4 (based on values in Table 4.1 and Table 4.3). Grain concentrations and TFs of the nutrients such as K, Mg, Zn, Sr, P, Ca, Fe, Mn and S fluctuated only little (except for the TFs of Mn and S vary strongly). The ratios for the nutrients K, Mg, and Zn in soils and grains were similar, those of P, Ca, and Mn fluctuated more in the soils. In

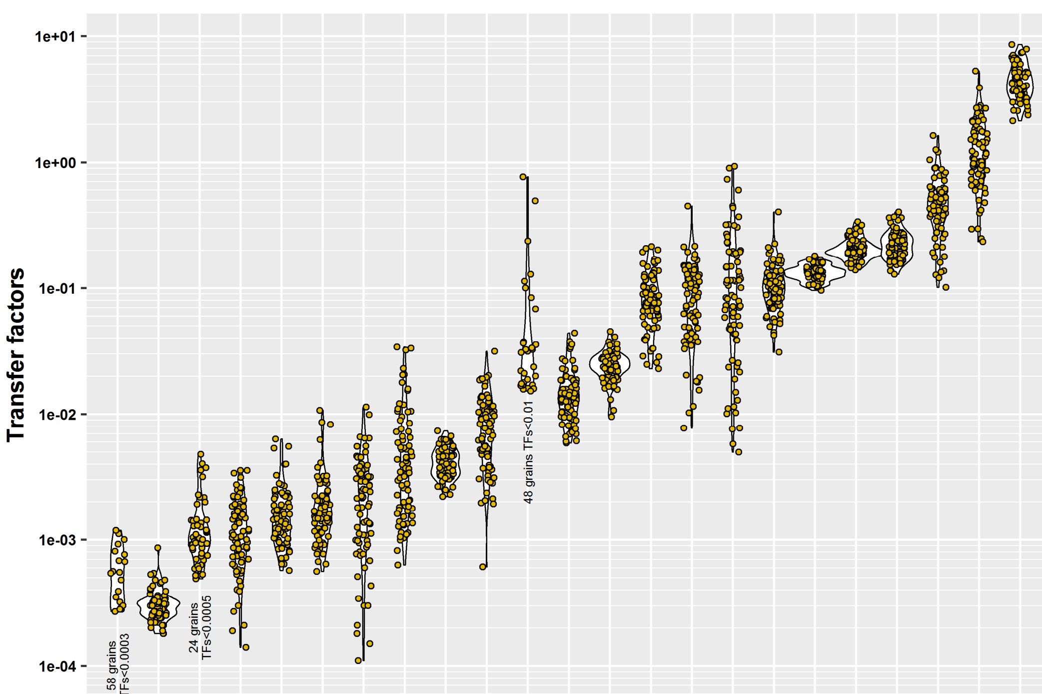

Fig. 4.4 Transfer factors of selected elements from soil to rice grain in the Mekong River area. Elements in rice with concentrations below detection limit such as Ti, Ce, La, Th, U, Al, Hf, Zr, V, Li, and Tl are not plotted

contrast, these ratios of some other nutrients (Na, Cu, and Mo) and harmful elements largely fluctuated. With most trace elements the ratios of grain concentrations are up to 50 times higher than those of soils. Uptake and fluctuation of the trace elements in grains cannot be explained only to a limited extent by the measured soil concentrations or combined soil factors such as Eh-pH, element sorption by and release from OM, clay minerals, Fe- and Mn-oxides/hydroxides. Mechanisms of specific uptake, translocation and fractionation of elements within the plant seem more important. In addition, other factors affect the element uptake such as nutrient demand, variety of rice, genotypes, and weather (Greger 2004). Unfortunately, an evaluation of the different influences on the element uptake was not possible in this study. However, despite lacking correlations between soil-pH (usually a dominant regulative for element uptake) and grain concentrations of Cd, Co, Cu, Mn, Ni, Pb, Zn, As, Bi, and Sb in our investigation, the influence of pH must be considered in future studies. The relation between soil parameters and trace element concentrations in rice grains would be more evident if the concentration ranges would be larger like in the Red River and Huong River areas (Nguyen et al. 2019).

Table 4.4 Ratios of maximum to minimum element concentrations in unpolished rice grains and soils as well as ratios of TF in Mekong River area (arranged in increasing order of TF)

Ratios	K	Mg	Zn	Sr	P	Ca	Fe	As	Mn	Na	Cu	Mo	Co	S	Ba	Pb	Rb	Cs	Ni	Cd
Grains	1.9	1.5	1.8	2.9	1.6	1.7	2.6	7.5	2.2	8.8	9.3	9.5	14	1.8	33	46	45	97	32	127
Soils	1.5	1.9	2.6	1.5	3.6	4.2	2.6	3.5	17	2.2	2.1	5.4	3.6	29	1.6	9.1	1.6	2.1	2.2	2.8
TF	1.9	2.4	3.1	3.3	4.0	4.7	4.5	7.5	9.4	11	13	16	19	23	26	54	58	100	31	186

Furthermore, it was not possible to detect relations between soil parameters and TFs of trace elements (Fig. 4.5), except for a few elements. The TFs of Cd showed negative trends with soil Fe- and Mn-concentrations. One explanation can be that increasing Fe- and Mn-oxide/hydroxide concentrations in soil competed for dissolved Cd by sorption, diminishing its concentration in the soil solution and uptake by the plants. The TFs of Mo were dependent on pH (weak positive correlation), LOI- and Al-concentration in the soils (weak negative correlations). Increasing molybdate sorption on OM and Al-phases towards lower soil pH (Fig. 4.3) may decrease the transfer of Mo into the plant (Smedley and Kinniburgh 2017). The TFs of Mn showed a highly significant negative correlation with Mn-concentration in soil (Fig. 4.5) following the trendline:

$$TF_{Mn} = 13.42*[Mn_{soil}] - 0.926 \qquad (R^2 = 0.87)$$

Increasing Mn concentrations with rising pH (Fig. 4.3) in soil led to less Mn in soil solution lowering the TF. In addition, decreasing OM-concentration at higher pH declined the Mn-solubility and plant availability. Both trends confirm the positive correlation between TFs of Mn and LOI (Fig. 4.5). The TFs of Zn increased with decreasing concentrations of Al- and Fe-phases in soils what is explainable with less sorption of dissolved Zn^{2+}, augmenting phytoavailable Zn in soil solution.

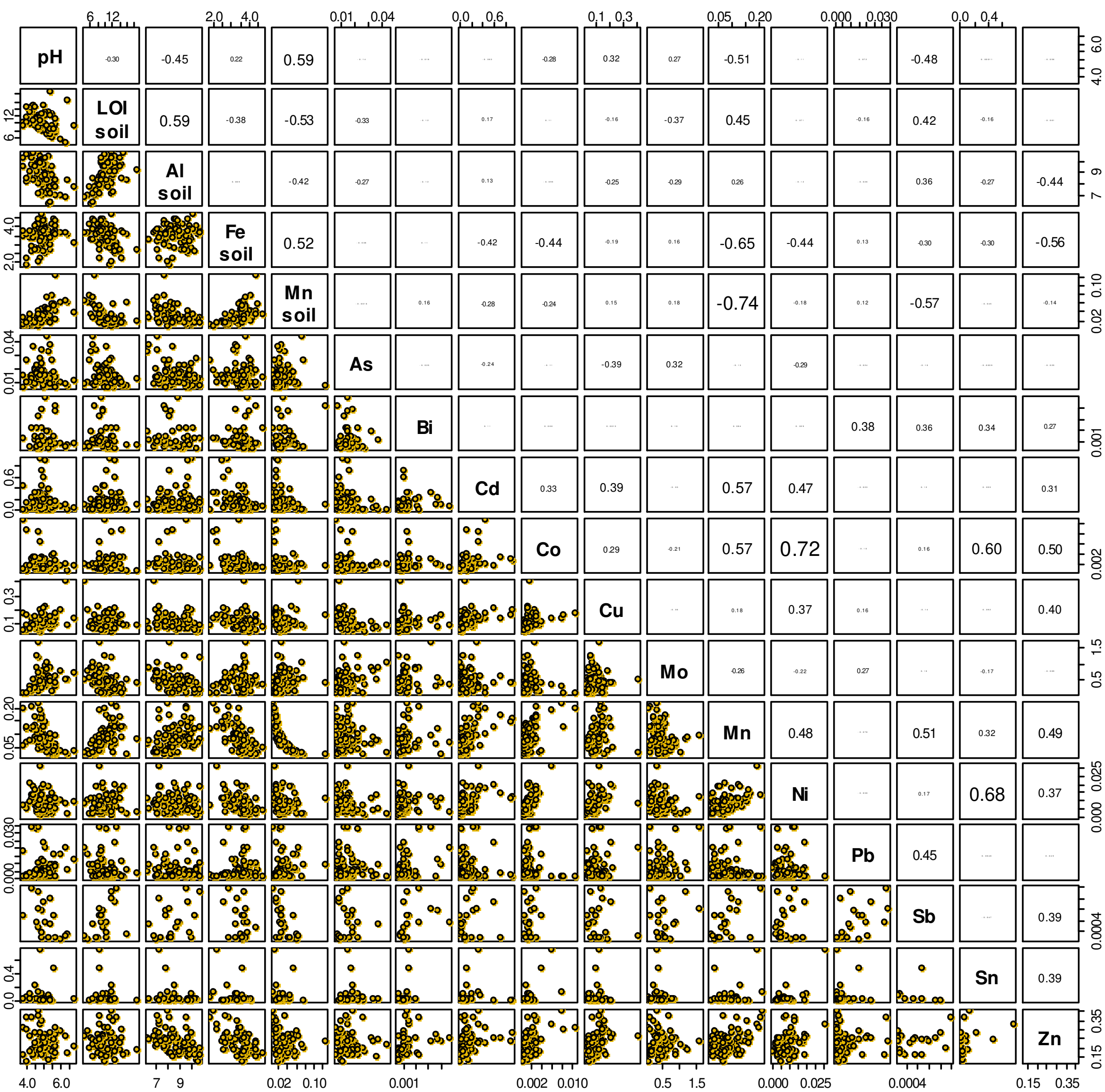

Fig. 4.5 Scattergram and correlation matrix for TFs of trace elements in the Mekong River area including relations between TFs and main element concentrations (wt. %) and pH in soils. Samples with grain concentrations below detection limit are not shown.

Comparing samples from all three river areas, the mean element concentrations in rice grains and transfer factors showed remarkable differences (Table 4.3), which are probably due to diverse soil properties and other factors like agronomic practices (phosphorus fertilizer applications, irrigation water), emissions, and rice cultivars. Huong River soils (mean pH = 4.4) and Mekong River soils (mean pH = 5.0) are more acidic than Red River soils (mean pH = 6.2). The low pH-value in Huong River soils led to remarkably higher grain concentrations of Ti, Ce, Cs, La, Li, Rb, Sr, Th, U, and V. In contrast, Mg-concentrations in grains were lower in more acidic soils, probably caused by less Mg on soil exchange sites diminishing its uptake. Compared to the Mekong area, the 1.5 times higher Ca-concentrations in rice from Huong and Red River area may be caused by Ca supply through fertilizer or irrigation water, in the Red River area additionally by higher soil Ca-concentration. The substantially higher concentration of Na in grains from the Mekong area may result from seaspray of the Pacific and Indian Ocean (no data available). Rice samples close to the Pacific Ocean contained twice as much Na than samples apart from the coast. Brackish groundwater and/or tide influences may deliver additional Na. The K-concentrations in soils and grains in the three areas were similar leading to comparable TFs.

Decreasing TFs and grain concentrations of As, Co, and Ni in the order Huong River > Mekong River > Red River area indicate that rising pH lowers the element uptake. Although As-anions are more soluble at higher pH, rising amounts of Fe-oxides/hydroxides lower the bioavailable As-concentration by sorption. The concentration of OM in Mekong River soils (mean LOI 10.3%) was much higher than in the other two areas (LOI 6.5%). More OM may lead to stronger solubilization of Pb and possibly of Sn by organic complexation, increasing the transfer into the grains. In contrast, the strong binding of Mo on soil OM may be the reason for lower Mo-concentration in grains from the Mekong area. A similar mechanism could be responsible for low Zn-concentration in Mekong rice grains. In all three river areas, mean Cd-concentrations were rising with mean P-concentrations in soils, indicating P-fertilizer as a Cd-source. The transfer into the grains was the highest in the Red River area where the soils contained the most Cd. The acidic soils of the Huong River area had the lowest Cd-concentration, but two times higher Cd-concentrations in the grains compared to the Mekong River area. This showed the strong impact of soil acidity on the Cd-uptake. The grain concentrations of the essential elements Fe and Cu in all three areas seemed not dependent on soil pH-values. The concentration trends described here can be roughly applied also to the TFs listed in Table 4.3.

The TFs of As for the rice grains from the Mekong River Delta ranged from 0.006 to 0.044 (mean 0.015; Table 4.3). They were similar to those in Yangtze River Delta (China) ranging from 0.002 to 0.053 (mean 0.020; Mao et al. 2019). The TFs of Cd for Mekong rice grains ranged from 0.005 to 0.93 (mean 0.15) and were slightly lower than those of Yangtze River with 0.012 to 1.51 (mean 0.224), even though Mekong River soils are more acid (mean pH 5.0) than Yangtze River soils (mean pH 6.8).

4.3.3 Rice composition and implications for health

As a major food for the Vietnamese population, the daily rice consumption supplies many essential nutrients to the human body. However, enrichment of toxic trace elements in paddy soils and corresponding rice grains may cause health risks for people - besides additions from other foods, drinking water and air. The average amount of rice that a Vietnamese adult consumes is 350 g for females and 446 g for males per day. An average Vietnamese woman weights 45 kg and a Vietnamese man 58 kg. The health risks from daily rice consumption were approached following two concepts: (1) the daily element intake doses from rice compared to Recommended Dietary Allowances (RDAs) and Tolerable Upper Intake Levels (ULs) for total food, drinking water, and supplements; (2) measured grain element concentrations compared to permissible Maximum Concentrations (MCs) in rice grains. The daily element intake (DEI) for a Vietnamese female or male was calculated as follows:

$$\text{DEI (mg day}^{-1}\text{)} = \text{Daily amount of rice consumption (kg day}^{-1}\text{)} \times El_{\text{rrain}} \text{ (mg kg}^{-1}\text{)}$$

In the first approach, the calculated daily intake amounts of nutrient and harmful elements by eating rice were compared with RDAs and ULs. The UL represents the highest level of daily element intake that is likely to pose no risk of adverse health effects - a definition given by the Food and Nutrient Board (FNB) of U.S. National Academies (Institute of Medicine 2001) and European Food Safety Authority (EFSA) (Table 4.5). RDAs and some ULs for females and males were taken directly from their publications. The ULs of the elements As, Cd, Co, Pb, Sb, and U were calculated for a Vietnamese adult as follows:

$$\text{UL (mg day}^{-1}\text{)} = \text{body weight (kg)} \times \text{daily tolerable intake level per kg body weight (mg day}^{-1}\text{ kg}^{-1}\text{)}$$

Please note that RDAs and ULs are valid for the consumption of all food, water, and supplement, with rice being only one element supplier.

Table 4.5 Daily element uptake by eating rice for a Vietnamese adult in mg day^{-1} in Mekong River area, in comparison with Red River area, Huong River area, the daily recommended dietary allowances and upper intake levels for total food and drinking water

Element	Intake by Female							Intake by Male						
	Mekong area			Huong River	Red River	FNB		Mekong area			Huong River	Red River	FNB	
	Min	Max	Mean			RDA	UL	Min	Max	Mean			RDA	UL
Ca	23	40	30	49	47	1000	2500	30	51	39	62	60	1000	2500
Fe	2	6	4	5	4	18	45	3	8	5	6	5	8	45
K	636	1212	908	1031	1019	-	-	810	1544	1157	1313	1298	-	-
Mg	354	547	451	434	488	310	-	451	697	575	553	622	400	-
Na	1.2	10.2	2.7	1.9	1.5	-	2300	1.5	13.0	3.4	2.5	1.9	-	2300
Zn	5.2	9.3	6.9	9.5	8.1	8	40	6.7	11.9	8.7	12.0	10.3	11	40
P	864	1374	1144	1132	1252	700	4000	1101	1751	1457	1443	1595	700	4000
As	0.03	0.2	0.06	0.09	0.05	-	0.096[b]	0.03	0.25	0.08	0.12	0.06	-	0.124[b]
Cd	0.001	0.065	0.013	0.030	0.041	-	0.016[a]	0.001	0.083	0.017	0.038	0.052	-	0.021[a]
Co	0.003	0.040	0.009	0.029	0.006	-	0.072[a]	0.004	0.051	0.011	0.037	0.008	-	0.093[a]
Cr	<0.04	0.22	<0.11	<0.04	<0.04	0.03	-	<0.05	0.29	<0.14	<0.05	<0.05	0.0	-
Cu	0.4	3.6	1.1	1.3	1.2	0.9	10	0.5	4.6	1.5	1.6	1.5	0.9	10
Mn	4.6	10.0	7.2	8.4	7.7	1.8	11	5.9	12.7	9.2	10.7	9.8	2.3	11
Mo	0.04	0.36	0.15	0.24	0.22	0.04	2.0	0.05	0.45	0.18	0.31	0.28	0.05	2.0
Ni	0.01	0.34	0.11	0.33	0.12	-	1.0	0.01	0.43	0.14	0.42	0.16	-	1.0
Pb	0.01	0.32	0.06	<0.01	<0.01	-	0.067[a]	0.01	0.41	0.08	<0.01	<0.01	-	0.087[a]
Sb	<0.0002	0.001	<0.0002	<0.0002	<0.0002	-	0.27[c]	<0.0003	0.001	<0.0003	<0.0003	<0.0003	-	0.35[c]
Sn	<0.02	0.90	<0.04	<0.02	<0.02	-	-	<0.03	1.15	<0.04	<0.03	<0.03	-	-
U	<0.00004	0.0001	<0.00004	0.0002	<0.00004	-	0.03[a]	<0.00004	0.0001	<0.00004	0.0003	<0.00004	-	0.04[a]

RDA: Recommended Dietary Allowance; UL: Tolerable Upper Intake Level for adults; FNB: Food and Nutrient Board of U.S. National Academies (Institute of Medicine 2001); [a]calculated from tolerable weekly intake given by the European Food Safety Authority (EFSA, var. years) for an average Vietnamese female and male; [b]Joint FAO/WHO Expert Committee on Food Additives (1989) mentioned by EFSA (2009a); [c]van Leeuwen and Aldenberg (2012); Red River and Huong River areas from Nguyen et al. (2019)

Looking at the results of the Mekong area in Table 4.5, rice provided only around 3% of daily needed Ca and 22% of needed Fe, although rice is the main nutritional base. Both elements must be supplemented from other foods such as meat, milk and drinking water. Magnesium intake by rice consumption surpassed the RDA. However, exceedance of magnesium intake does not pose risks for healthy individuals (National Institutes of Health 2018). The remaining nutrient elements Cu, Zn, P, Mn, and Mo are sufficiently supplied by rice but are far below the ULs. The Na-uptake has no RDA but is far below UL.

The provisional tolerable intake doses of inorganic As for an average Vietnamese female is 0.096 mg day^{-1} and 0.124 mg day^{-1} for a male (calculation based on older limits from of Joint FAO/WHO Expert Committee on Food Additives, cited in EFSA 2009a). Although in the Mekong area the mean As-intake was lower than the tolerable dose, 12% of the rice samples exceeded the As-doses for both genders causing potential health risks. Other As-sources such as drinking water and foods increase the doses. Compared to the results from Red River and Huong River areas (Nguyen et al. 2019), rice from the Huong River area showed the highest potential health risk. Using the recent tolerable As-doses proposed by EFSA (2009a), the maximum allowed As-intake for a Vietnamese woman would range from 0.014 to 0.360 mg day^{-1} and for a man from 0.017 to 0.464 mg day^{-1}. All As-intake values calculated in this study were within those ranges, but all values are higher than the lowest tolerable limit. There were systematic studies of health risks by drinking water with more than 10 µg/L As in the Mekong area, where more than 0.5 million people are at risk of chronic arsenic poisoning (Berg et al. 2007; Erban et al. 2013; Merola et al. 2015), but Specific symptoms of As poisoning, however, have not been described (Berg et al. 2007; Erban et al. 2013; Merola et al. 2015). A corresponding study about As-related health risks from rice consumption was hitherto lacking as well as a study for the combined effects from both sources.

The ULs for Cd are 0.016 and 0.021 mg day^{-1} for a Vietnamese female and male respectively. 29% of studied samples exceeded the Cd-threshold for both female and male; 9% surpassed twice the threshold. The risk of Cd-toxicity in Mekong River area was remarkably lower than in the other two areas.

The ULs for Pb are 0.067 and 0.087 mg day^{-1} for a Vietnamese female and male respectively. 27% of the rice samples are higher than the ULs for both female and male, whereby 10% of the samples were more than 2-times higher. It seems, while the Pb intake from rice grown in Red and Huong River areas is not a problem, it presented a serious issue in the

Mekong area. Healthwise, the daily intake of Co, Cr, Sb, and U by eating rice seems safe for all three areas since intake amounts were far below tolerable limits.

In the second approach, the measured concentrations of As, Cd, and Pb in rice grains, shown as maps in Fig. 6, were compared with the MC-values proposed by FAO/WHO (2014) and European Union (2006). These organizations recommend a MC of 0.2 mg kg^{-1} inorganic As for adults and 0.1 mg kg^{-1} for young children. According to Suriyagoda et al. (2018), the inorganic As-portion in rice grains is 54% of total As. This corresponds to the MC of 0.37 mg kg^{-1} total As for adults and 0.19 mg kg^{-1} for young children. Compared to these limits, 5% of the Mekong samples would pose a health risk to adults and about 37% to young children. All Red and Huong River rice samples showed total As-concentrations below the MC for adults, but for children 75% of Huong River samples and 26% of Red River samples were above the MC and may cause As-related health risks. It must be considered, that in the compilation of Rahman and Hasegawa (2011) the portion of inorganic As in rice ranged broadly between 31 and 100% depending on rice species and climate.

24% of the Mekong rice samples exceeded the MC of 0.2 mg Pb kg^{-1}, 10% contained more than twice as much. All Pb-concentrations in the Huong and Red River rice were below the MC. All Cd-concentrations of Mekong and Huong River rice samples were lower than the MC of 0.2 mg kg^{-1}, but 16% of Red River samples surpassed the MC.

The inconsistent results of the MC concept and of the UL concept stress the need to accommodate the MCs of As, Cd, and Pb in rice grains and the ULs for total food, water, and supplements.

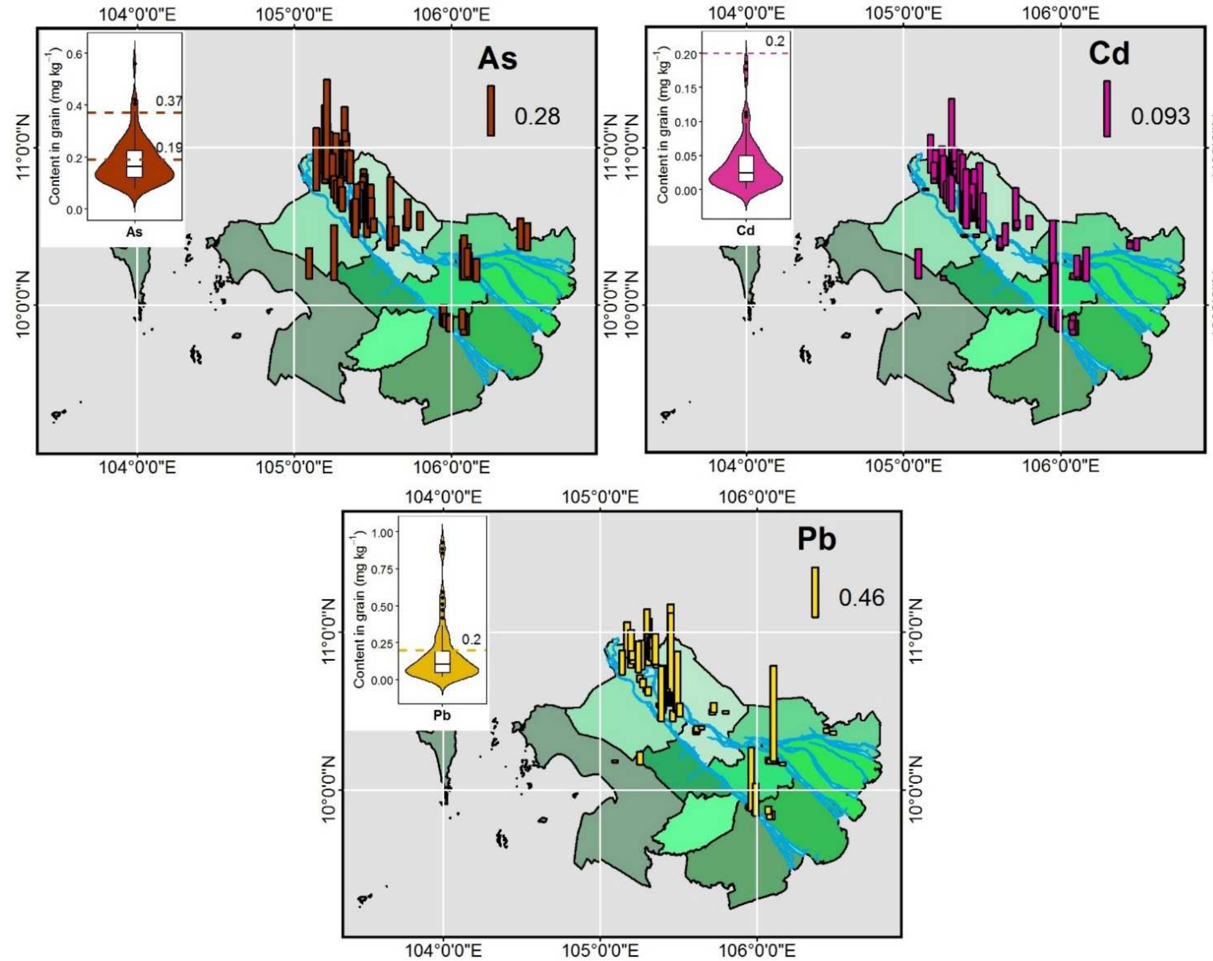

Fig. 4.6 Map of As, Cd, and Pb concentrations in rice grain in the Mekong River Delta and their allowable maximum levels (in mg kg^{-1})

4.4 Conclusions

The parent material of paddy soils along Mekong River in southern Vietnam consists of alluvial sediments, delivered from Tibetan Plateau and surrounding mountains. Most of the soil samples were not or only slightly contaminated by harmful elements. Compared to average shale, the 80 investigated paddy soils were naturally enriched by Ce, Th, As, La, U, Sn, Cs, and Bi. Fertilizer and emission inputs may cause slight enrichments of P, Cd, and Pb. Multiple linear regression models can help to reveal the relationship between trace element concentrations and soil phases. The soil parameters with the strongest influence on trace element concentrations were:

- Fe-phases: Co, As, Cd, Sb
- Al-phases: Tl, V, Bi, Sn, Pb, U, Ni, Zn, Cu

- Organic material (LOI): Mo

Strong positive correlations of these elements with the mentioned soil phases point to structural binding, sorption and/or co-precipitation processes.

11% of all Mekong soil samples exceeded the permissible As-limits for Vietnamese agricultural soils. One sample had extraordinary high concentrations of Pb (190 mg kg^{-1}) and of Sb (6.5 mg kg^{-1}) greatly exceeding their geochemical background values. All other critical elements were far below their permissible soil limits.

Soil parameters are partially responsible for element concentrations in rice grains. However, in the Mekong River area the element TFs showed no correlations with soil parameters, except for the TF of Mn, which correlated strongly with soil Mn-concentrations, following the trendline $TF_{Mn} = 13.42*[Mn_{soil}]^{-0.926}$ ($R^2 = 0.87$). Larger ranges of soil parameters and/or stronger toxic element enrichments would make the transfer of toxic elements into rice grains more obvious.

Based on the Tolerable Upper Intake Levels UL of As for total daily food and drinking water, 12% of studied rice samples in the Mekong Delta area may cause As-related health risks for adults. 29% of the rice grain samples surpassed the ULs of Cd. 27% of the samples exceeded the ULs of Pb. On the basis of maximum concentration MC for inorganic As, Cd, and Pb in rice grain, 5% of the studied rice grains surpassed the MC of inorganic As for adults and 38% that for young children. 24% of studied rice samples exceeded the MC of Pb. Cd was below the MC in all the rice samples.

To sum up, in some parts of lowland river areas in Vietnam, the intense continuous rice consumption may lead to chronic exposure to As, Cd, and Pb and potential health risks of the local population.

Considering the importance of rice as the main staple food for billions of people worldwide, four important research priorities result from our investigation:

1. High health risks from As, Cd, and Pb exposure by eating rice ask for urgent revision and harmonization of the daily element intake dosis concept (UL) with the maximum element concentration concept (MC). In addition, the combined effects of rice and drinking water on the As-intake should be studied in detail for different areas.

2. Soil concentrations of As, Cd, and Pb do not allow to predict the expected concentrations in rice grains, even if soil pH, mineral and organic phases are taken into consideration.

Surprisingly, rice grains growing in non- or low-polluted paddies may surpass critical health levels of As, Cd, and Pb. Thus, limits for critical elements in paddy soils cannot be the standard to guarantee uncontaminated rice. Not the soils but the rice grains should be measured in different areas to get information about health relevance.

3. The research on how to minimize the translocation of As, Cd, and Pb from the soils into the rice grains should be intensified (see overviews of Rizwan et al. (2016) for Cd, Suriyagoda et al. (2018) for As).
4. Rice cultivars with reasonable yield should be systematically tested for low uptake of critical elements. Such cultivars should be preferentially planted in critical areas.

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4.6 Supplementary material

The supplementary material of this paper are introduced in Appendix A2

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Chapter 5

Transfer of nutrient and toxic elements from paddy soils into rice plant parts (Oryza sativa) in Vietnam and health risk assessments for the population

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Abstract

The uptake of elements from soils into shoot, husk, and unpolished grain of rice plants are investigated in Mekong, Huong and Red River areas in Vietnam. The influence of soil parameters on transfer factors (TF) of elements from soil into plant parts and the whole aboveground plant are evaluated. The TF of most elements decrease in the order shoot > husk > grain. Exceptions are Mg, S, Cd, Cu, Zn, and Mo, whose TF diminishes in the order shoot > grain > husk, and P whose TF declines in the order grain > shoot > husk. The translocation of health relevant elements like As, Cd and Pb into the different plant parts is described in dependency on the soil parameters pH, contents of organic matter, Fe- and Mn-phases, and clay minerals. Lead transfer into rice grains increases in soils rich in organic matter. Health risk assessment approaches for the average daily consumption of rice are performed for non-cancer risk (Hazard Index HI) with the elements As, Cd, Pb, Co, Cu, Mn, Mo and Ni as well as for cancer risk with As and Pb (Incremental Lifetime Cancer Risk ∑ILCR). All rice grains exceed the safe HI-index (below 1). 81% of the samples are within the level of concern ranging between $1.4 < HI < 5$. 18 % vary between $5 < HI < 8.4$, although their soils show only little pollution. One sample from a contaminated site even reaches HI 24. Cadmium, As, Mn, and Pb are the main elements causing non-cancer risks for rice-consuming people. The cancer-risk values ∑ILCR of As and Pb are between 0.9×10^{-3} to 6.4×10^{-3} (mean 2.2×10^{-3}) and are considerably higher than the safe threshold of 10^{-4} to 10^{-6}. Arsenic is the dominant factor for cancer risk. People living in Red River and Huong River areas face mainly As- and Cd-related health risks from rice consumption. People in the Mekong River area suffer from additional Pb exposition.

Keywords rice • paddy soils • element transfer • health risk • Vietnam

5.1 Introduction

Rice is a principal daily energy and protein-supplying source for most of the Asian population. On the other hand, rice can be a prominent source for harmful elements such as As, Cd, and Pb. Rahman and Hasegawa (2011) stated that rice is the food with highest accumulation of As compared to other agricultural products. High As concentrations in rice and drinking water were recognized as the main reasons for serious chronic diseases of millions inhabitants in Bangladesh and West Bengal, India (Bhattacharya et al. 2010; Abedin et al. 2002; Khan et al. 2009). Due to the easy Cd uptake of rice plants, rice consumption can also cause illnesses (Rizwan et al. 2016). 50% of rice samples from Cd-polluted paddy soils in Tak Province, Thailand, exceed the concentration of 0.4 mg Cd kg^{-1} and up to 90% surpass the permissible threshold of 0.2 mg Cd kg^{-1} (Sriprachote et al. 2012; Simmons et al. 2005). Lead may also have a potential health risk in different rice-producing areas as recognized by Norton et al. (2014), Shraim (2017), and Fakhri et al. (2018). Chronic exposure to these elements causes deleterious health effects resulting in increasing carcinosis, harmful impacts on heart, bones, skin, kidney, and neurological disorders (EFSA 2009, 2010; Smith et al. 2006; Kumarathilaka et al. 2018; Jaishankar et al. 2014).

Soils enriched with potentially toxic elements are often assumed to cause higher accumulation in plants. The element concentration in paddy soils originates from geologic sources, but also from anthropogenic additions like mining and industrial operations, agricultural practices (fertilizer and pesticides), and/or using contaminated wastewater for irrigation. However, the accumulation of an element in a plant depends on the plant species or cultivar, its concentration in solid soil phases, type of bonding and its concentration in interstitial solution. According to Xiao et al. (2017), the soil bioavailable metal concentration of Cd, Cr, and Ni and microbial activities have a major impact on their accumulation in rice grains. Environmental effects such as the site, the crop season in combination with the kind of cultivars may explain most of the variation of As and Cd concentrations in rice grains (Chi et al. 2018). Soil parameters like pH, Eh, CEC (cation exchange capacity), organic matters, Fe-, Al-, Mn-oxides/hydroxides, and clay minerals substantially affect elements' transfer factors (Young 2013; Kabata-Pendias 2011). Iron-rich plaques along rice roots are able to fix the two species As(V) (44 - 66%) and As(III) (34 - 56%) (Seyfferth et al. 2011) and can diminish the As uptake into the plant (Suriyagoda et al. 2018). Under reducing conditions mediated by microorganisms, As(V) in Fe-plaques can be reduced to more phytoavailable As(III)-forms

(Seyfferth et al. 2014; Hu et al. 2015). Depending on rice genotypes, Islam et al. (2016) observed a considerable enhancement of the As transfer into rice under reducing conditions. Simmons et al. (2005) identified in submerged paddy soils downstream of a mineralized area with sulfidic ore deposits in Thailand precipitation of CdS and ZnS due to the reduction of sulfate (SO_4^{2-}) to sulfide (S^{2-}). However, these precipitates might be transformed under oxic conditions into phytoavailable Cd^{2+}, Zn^{2+}, and SO_4^{2-}. Together with the resulting soil acidification, this may lead to a considerable uptake into rice grains. Xiao et al. (2017) assumed that the uptake of Pb by rice grains is not determined by its bioavailability in soils, but rather by multi-metal interactive effects.

Some other external factors such as plant density, temperature, and light may also affect the element uptake but their effects are intricate and only poorly understood (Greger 2004). Interaction with Zn, Fe, Se, Si, and liming limits the uptake and translocation of Cd from root to shoot (Rizwan et al. 2016; Wan et al. 2018). Also according to Greger (2004), the fluid-transporting process from root to other plant parts are fostered by some factors: transpiration of water, root pressure, cation exchange at cell walls of the xylem vessel, formation of complexes with amino acid (Cu), with histidine and peptide (Ni), and chelates with organic acids (Zn). Due to the powerful binding on cell walls, most elements are mainly located in the roots and only smaller portions are transferred to other parts such as stem, leave, and grain. For the soil-rice system, the concentrations of Cr, Fe, Co, Ni, Cu, Cd, Zn, As, Ba, and Pb generally decrease in the following order: soil > root > shoot > grain (Du et al. 2018; Biswas et al. 2013; Bhattacharya et al. 2010). Satpathy et al. (2014) identified higher Cd and Mn concentrations in shoot compared to root. In addition, the kind of cultivar also determines the element distribution in plant parts as shown for Cd and As (Liu et al. 2011; Islam et al. 2016; Duan et al. 2017; Li et al. 2017).

After cropping, roots and stubbles are left in the fields and become a source of organic material (OM) for paddy soils. Depending on the area, rice straw may be taken away for animal bedding, cooking, or soil conditioning materials. Husk, the remaining part after rice peeling, is increasingly applied for many purposes such as the production of heat or electricity, activated carbon, fertilizer, bricks, ceramics or sorbents for heavy metals (Kumar et al. 2013). Often the fields are burned after harvesting. Both, the export and burning of organic material deteriorate the humus balance.

Vietnam is mainly an agricultural country and one of the world's largest rice producers. The biggest granaries of the country are the Mekong River Delta in the south and the Red River Delta in the north, where abundant water boosts the irrigation. In addition, the annual flooding delivers fertile suspended material that settles in the rice fields. As a result, parent material of paddy soils is mainly alluvial sediment rich in organic matter. Some of the paddy soils in Vietnam are polluted by heavy metal(loid)s such as As, Cd, Cr, Cu, Pb, and Zn from industrial and mining activities leading to the contamination of rice grains (Huong et al. 2008; Phuong et al. 2010; Ha 2011; Vinh et al. 2012). However, most of the As contamination in paddy soils and rice grains comes from natural sources influenced strongly by redox processes as described by Seyfferth et al. (2014) and Nguyen et al. (2019a, b). 11% of Mekong River soils and 92% of Red River soils exceed the Vietnamese As limit of 15 mg kg^{-1} for agricultural soils. 5% of unpolished rice grains in the Mekong River area surpass the permissible maximum inorganic As concentration of 0.2 mg kg^{-1} for adults while all rice samples from the Red River area are below that limit (Nguyen et al. 2019a, b). 37% of the Mekong River rice and 26% of the Red River rice samples exceed the permissible maximum concentration of 0.1 mg kg^{-1} for children. Even in uncontaminated soils, Cd and Pb concentrations in rice grains can be higher than their permissible maximum limits of 0.2 mg kg^{-1} in rice. 12% of Red River rice grains exceed the Cd limit but no sample of the Mekong River area surpasses this limit. 24% of Mekong River rice grains trespass the Pb limit of 0.2 mg kg^{-1}, but no sample from the Red River area. Different soil conditions among these areas should be a reason for toxic element enrichments within the grains (Nguyen et al. 2019a, b). Most of current studies just focus on the uptake of a few harmful elements, but do not include the transfer of the other elements into rice plants. Understanding of the influence of soil factors on element translocation to and within the rice plant is crucial to mitigate their uptake and to protect human health.

The research purpose of this study is to evaluate a) the translocation of the phytoavailable/bioavailable portion of elements from soil into the aboveground parts of rice plants under the influence of soil parameters such as pH, organic material, Al-, Fe-, and Mn-oxides/hydroxides; b) the differing accumulation in shoot, husk, and rice grain; c) health risk assessment of rice consumption for cancer and non-cancer risks.

5.2 Materials and methods

5.2.1 Sampling, digestion, analysis and quality control

The rice plant and corresponding soil samples were collected along three river systems in Vietnam including the Red River Delta in the north (19 sites), Huong River in the center (4 sites), and Mekong River Delta in the south (78 sites). The sample locations are shown in Fig. 2.1 (coordinates of the samples are shown in Table A3.1 in Appendix A3). All samples were taken within 10 days before harvesting time. The 23 rice plant samples of the Red River and Huong River areas were separated into shoot (stalk and leaves combined), husk, and unpolished rice grain. Roots and stubbles were left in the fields. 78 rice samples of the Mekong River area were split into husk and grains. The soil samples were taken within the root zone to a depth of 10 cm.

The plant samples were dried at 60^0C, the soil samples at 105^0C. All samples were pulverized into grain sizes <63 µm by a Fritsch© agate ball mill before analyzing.

The soil pH-values were determined in a 1:2.5 (w/v) mixture of the air-dried unground soils and 0.01 M $CaCl_2$ solution by using the glass electrode ProfiLine pH/mV-Meter 197. The Loss on Ignition (LOI), representative for organic matter and structural water in the soil samples, was determined as weight loss after heating the samples to 530°C for 24 hours.

The milled samples were completely digested in a mixture of ultrapure concentrated acids HNO_3 (65%), HF (40%) and $HClO_4$ (72%) in closed ultra clean PTFE vessels (PicoTrace®, Göttingen, Acid Sample Digestion System DAS 30). The clear digestion solutions were then measured by ICP-OES (Inductively Coupled Plasma - Optical Emission Spectrometry) Agilent 5100 VDV and by ICP-MS (Inductively Coupled Plasma Mass Spectrometry) Thermo Scientific iCAP Q to get the total element concentrations. For accuracy and precision, the data were validated by in-house and international reference materials: GSJ-JA-2 (Andesite) and GSJ-JLk-1 (Lake Sediment) for soil concentrations; NCS-DC-73349 (Branches and Leaves of Bush), WEPAL-IPE 126 (Maize plant), WEPAL-IPE-168 (Sunflower) for grain concentrations. Most selected elements have deviations of below 5% from the recommended values of the reference materials.

5.2.2 Correction for adhering particles, calculation of transfer factors

To evaluate more exactly the element transferability from soil into plant, the physiological or biological concentrations in the different plant parts are calculated. The measured concentration in plant material is composed of the physiological element amount within the plant plus the additional amount caused by adhering soil and dust particles. Because of lacking information about the composition of atmospheric dust at a single sample location, the soil material of the sampling site is used as representative for the correction of adhering material (Pospiech et al. 2017). This correction is important for concentrations in shoot and husk, but can be neglected for the grains because they are protected by husks against adhering dust or soil. Titanium is chosen as indicator element for the adhering soil portion because plants take up Ti in only negligible quantities.

One approach to calculate the portion of adhering soil (x) of a plant part is dividing the measured Ti concentration in that part ($Ti_{measured,plant\ parts}$) by the Ti concentration in the corresponding soil (Ti_{soil}) (Pospiech et al. 2017):

$$x = \frac{Ti_{measured,plant\ parts}}{Ti_{soil}}$$

The physiological concentration of an element in a plant part ($El_{physiological,plant\ parts}$) can be calculated from the measured concentration ($El_{messured,plant\ parts}$) and adhering soil portion (x) as follows:

$$El_{physiological,plant\ parts} = \frac{El_{measured,plant\ parts} - x * El_{soil}}{1 - x}$$

Transfer factors (TF) or bioaccumulation factors of elements are the ratio of the physiological element concentration in plant parts ($El_{physiological,plant\ parts}$) to its concentration in soil (El_{soil}):

$$TF = \frac{El_{physiological,plant\ parts}}{El_{soil}}$$

Transfer factors are calculated for shoot, husk, grain, and the whole aboveground plant without roots and stubbles. The measured and physiological concentrations and transfer factors in plant parts are listed in Tables S2 to S5 in the supplement material of this paper.

5.2.3 Exposure and health risk calculations

Chronic risk exposure from rice consumption for people's health can be evaluated on the basis of indices of lifetime cancer risk and of lifetime non-cancer risk (Järup 2003; Mulware 2013). These indices are based on the Chronic Daily Intake (CDI) (mg kg^{-1} body weight day^{-1}) (USEPA 1989) which can be calculated as follows:

$$CDI = (CF \times IR \times EF \times ED) / (BW \times AT)$$

where *CF* is the harmful element concentration in rice (mg kg^{-1}); *IR* is the average daily rice consumption of 0.398 kg day^{-1} for Vietnamese adults (Nguyen et al. 2019a); *EF* is the exposure frequency (365 days $year^{-1}$); *ED* is the exposure duration (70 years); *BW* is the Vietnamese average body weight of 52 kg (Nguyen et al. 2019a); *AT* is the average period of exposure days to hazardous element intake.

Non-cancer risks

The chronic non-cancer risk approach is used to evaluate non-carcinogenic health effect of harmful elements from different sources. For rice, As, Cd, Pb, Mn, Co, Ni, Cu, and Mo are considered the most potentially harmful elements causing adverse health effects. The Target Hazard Quotient (*THQ*) describes the exposure to an element and can be calculated as follows:

$$THQ = CDI / RfD$$

RfD is the chronic reference dose (mg kg^{-1} b.w. day^{-1}) of a harmful element and represents the maximum permissible element amount taken up from all sources (food, water, air etc.). The *RfD* values of elements for this paper were calculated by using data compiled by Nguyen et al. (2019a, b).

The Chronic Hazard Index (*HI*) for non-cancer factors is the sum of the single *THQ* and represents the total non-carcinogenic hazard attributable to exposure:

$$HI = \sum_{n=1}^{\infty} THQ$$

At HI ≥ 1, potential health effects must be worried even if the exposure for every single element is below its RfD (USEPA 1989). Nordberg et al. (2015a) notice that the HI-approach is simple but limited in its scope because it may either under- or over-estimate the risk from multiple chemical exposures.

Cancer risks

Incremental Lifetime Cancer Risk (*ILCR*) is an index to estimate the incremental probability of an individual cancer progression over a lifetime (USEPA 1989). The ILCR of a harmful substance is computed as follows:

$$ILCR = CDI \times SF$$

where *SF* is the Slope Factor. It represents an upper estimate of the probability of an adverse response to the lifetime intake of a carcinogenic substance by ingestion, inhalation or dermal contact (USEPA 1989) $(mg/kg\text{-}day)^{-1}$. The three elements As, Cd, and Pb are considered key carcinogenic risk factors for low dose element intakes. However, there is insufficient information about the slope factor of oral Cd intake so Cd is excluded. In this study, the ILCR of As and Pb are estimated for eating unpolished rice with slope factors $SF_{As} = 1.5$ and $SF_{Pb} = 0.0085$ $[mg\ kg^{-1}\ day^{-1}]^{-1}$ (OEHHA 2011).

Cumulative cancer risk ($\sum ILCR$) is the sum of single lifetime cancer risks, which are restricted here to the carcinogens As and Pb:

$$\sum ILCR = ILCR_{As} + ILCR_{Pb}$$

USEPA (1989) proposes a healthy safe level when ∑ILCR is below10^{-6} and acceptable levels at values from 10^{-6} to 10^{-4}.

5.3. Results and discussion

5.3.1. Soil composition

Main soil parameters such as pH-/Eh-values, organic matter (OM, LOI as proxy), Al (clay minerals), and Fe- oxides/hydroxides determine the behavior and availability of elements in soil solution and their uptake by rice plants. Statistical data for paddy soils in three important river areas in northern, central, and southern Vietnam are compiled in Table 5.1 (detailed data are listed in Nguyen et al. 2019a, b). The influence of soil parameters on the element concentration can be summarized as follows:

- Organic matter (OM) has a large, negatively charged surface area. Therefore, OM is able to hold cationic elements by sorption and to lower their plant availability. In addition, some organic ligands can form soluble complexes with trace elements, promoting their plant uptake. In an oxidizing environment, Fe- oxides/hydroxides may sorb or co-precipitate trace elements. During the dissolution of this phase at low pH-values, adsorbed elements either may be released and become bioavailable or may be re-adsorbed by the organic material. For example, As-enriched Fe-oxides/hydroxides are dissolving towards lower pH-values and sorbed arsenate ions are released. These arsenate ions may be reduced to arsenite ions and even to methylated As(III)-compounds (Kumarathilaka et al. 2018).

- In acidic soils, protons may compete with cationic trace elements sorbed on soil phases and release them into solution. Additionally, the dissolution of Fe-oxides/hydroxides at low pH-value liberates their trace elements. Both mechanisms provide trace elements for an easy uptake by rice plant.

Paddy soils in the Huong and Mekong River areas are mainly acidic with mean pH-values of 4.4 and 5.0, respectively. Soils in the Red River area show average near-neutral pH-values at 6.2. The relation between pH and the concentrations of OM, Al, Fe, and Mn in soils can be described as follows (plotted in Fig. A3.1 in Appendix A3):

- Manganese in soils is positively correlated with pH-values. At lower pH-values, some of the Mn may be dissolved from Mn-containing mineral phases like clay minerals, Fe- and Mn-oxides/hydroxides. At the relatively high pH-value soils in the Red River area, the Mn-containing phases seem to be stable and no Mn has been lost. Mn-oxides/hydroxides in paddy soils are unlikely to exist for the following reasons: First, the Mn concentration in the soils is below 800 mg kg^{-1} of which most of it is bound in silicates and little in Fe-oxides/hydroxides. Second, the soil pH-values in all paddy soils are below 7.3 and mostly reducing – conditions under which the Mn-oxides/hydroxides are not stable.
- Iron is not significantly correlated with the pH-value. Some of the Fe is bound in the framework of silicates, but only the fraction bound in Fe-oxides/hydroxides is sensitive to reductive dissolution or acidification. Suboxic and anoxic sediment samples taken along the Red River contain between 1 and 77 µmol/g Fe that is bound as Fe-oxides/hydroxides (corresponding to 0.008 to 0.61 wt. % Fe_2O_3). Their highest concentrations are identified in the most recent sediments (Jessen et al. 2012; Postma et al. 2016; Sø et al. 2018). In the Mekong River Delta, however, the upper meters of sediments contain between 27 to 50% reducible Fe (up to 3.4% Fe_2O_3), meaning that this Fe-fraction is bound in oxides-hydroxides (Stuckey et al. 2015a; Wang et

al. 2018). Depending on the reactivity of the Fe-oxides/hydroxides and of the OM, not all of the oxidic iron phases are reducible at low Eh-values (Stuckey et al. 2015a, b).

- The Mekong River soils contain more OM (mean LOI of 10.3%) than the Red River soils (6.5%) and Huong River soils (6.4%). The LOI concentrations tend to increase with decreasing pH-values. Acidic groups in organic matter may cause some of the acidity in soil (McCauley et al. 2017). Lower pH-values conditions are less favorable for the OM oxidation leading to higher OM contents. Another reason for the higher OM content in Mekong River soils may be the shorter time span for its oxidation due to three cropping seasons per year compared to only two cropping seasons further in the north. In addition, three harvestings release more roots and stubbles in the soils increasing the OM content.
- Soil pH-values negatively correlate with the Al concentrations similar to OM. Al and OM are positively correlated with high significance. Reasons are: The finer the suspension in the irrigation water is, the higher the concentrations of Al-rich clay minerals and of OM are. In addition, clay minerals contain structural water increasing the LOI concentration.

Table 5.1 Average element concentrations in soils and rice plant parts (mg kg^{-1}, except for LOI in wt. %). Ratio represents the mass ratio of shoot, husk, and unpolished grain to the whole aboveground plant. (Data of soils and grains from Nguyen et al. (2019a, b)

Ele-	**Soil** (n = 101)				**Shoot** (n = 23)				**Husk** (n = 101)				**Grain** (n = 101)				**Plant** (n = 23)			
ment	Red	Huong	Mekong	Mean	Red	Huong	Mekong	Mean	Red	Huong	Mekong	Mean	Red	Huong	Mekong	All	Red	Huong	Mekong	All
Ratio	-	-	-	-	0.41	0.47	-	0.42	0.12	0.11	0.12	0.12	0.47	0.43	0.46	0.46	1	1	1	1
pH	6.2	4.4	5.0	5.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LOI	6.5	6.4	10.3	9.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Al	75850	74854	87130	84522	<4	<4	-	<4	<4	<4	<4	<6	<4	<4	<4	<4	<4	<4	-	<9
Ca	5689	2180	3725	4033	5219	3915	-	4992	1099	1388	749	840	134	139	87	98	2275	2079	-	2241
Fe	44221	34523	34773	36541	70	163	-	86	23.8	28.6	20.0	21	10.8	12.9	10.3	10.5	37	88	-	46
K	20081	19786	19680	19760	35711	22842	-	33473	3878	5184	4010	4032	2897	2945	2595	2666	16103	12615	-	15496
Mg	8142	5772	6460	6750	2671	3013	-	2731	311	415	324	325	1384	1240	1290	1305	1789	1974	-	1821
Mn	526	254	304	344	696	848	-	723	256	252	177	195	22	24	21	21	328	434	-	347
Na	5295	2991	4587	4657	346	541	-	380	20.1	8.6	52.5	44.7	4.2	5.5	7.6	6.9	146	238	-	162
P	865	487	780	785	1139	1493	-	1200	1308	1104	1411	1380	3545	3235	3269	3319	2308	2219	-	2293
S	651	516	930	861	1635	2352	-	1760	690	554	625	634	1089	1051	880	926	1269	1620	-	1330
Ti	4854	4856	4808	4819	0	0	-	0	0	0	0	0.0	0	0	0	0	0	0	-	0
As	22.5	13.6	12.6	14.8	2.7	3.2	-	2.82	0.41	0.78	0.30	0.34	0.21	0.27	0.18	0.19	1.26	1.74	-	1.34
Ba	417	460	394	402	93	125	-	99	19.2	21.5	7.1	10.0	1.24	1.51	0.51	0.69	41	61	-	45
Bi	0.88	0.56	0.40	0.51	0.010	0.008	-	0.009	0.0058	0.0035	0.0006	0.0017	<0.0004	0.0017	<0.0004	<0.0004	0.005	0.005	-	0.005
Cd	0.37	0.25	0.27	0.29	0.44	0.45	-	0.44	0.103	0.155	0.028	0.047	0.120	0.085	0.037	0.055	0.254	0.255	-	0.254
Ce	90	83	81	83	0.123	0.202	-	0.137	0.0714	0.0537	0.0230	0.0333	<0.0009	0.0058	<0.0007	<0.001	0.053	0.102	-	0.061
Co	15.7	13.3	13.2	13.8	0.17	0.79	-	0.28	0.063	0.126	0.045	0.052	0.016	0.083	0.025	0.026	0.085	0.422	-	0.144
Cr	69	39	94	86	0.97	0.71	-	0.92	0.38	0.39	0.17	0.22	<0.1	<0.1	<0.1	<0.24	0.46	0.40	-	0.45
Cs	8.1	6.3	11.2	10.3	0.191	1.062	-	0.343	0.102	0.403	0.039	0.066	0.038	0.426	0.029	0.046	0.10	0.72	-	0.21
Cu	48	27	30	34	3.52	3.51	-	3.52	2.23	2.21	1.99	2.04	3.35	3.58	3.26	3.29	3.3	3.4	-	3.3
Hf	4.1	3.8	4.1	4.1	0.0068	0.0078	-	0.007	0.0040	0.0020	0.0044	0.0042	<0.0002	0.0005	<0.0002	<0.0002	0.0033	0.0042	-	0.004
La	44	41	41	41	0.092	0.102	-	0.094	0.0415	0.0267	0.0168	0.0218	<0.0005	0.0032	<0.0004	<0.0005	0.040	0.052	-	0.042
Li	40	27	50	47	0.061	0.090	-	0.066	0.0207	0.0202	0.0240	0.0232	<0.006	<0.014	<0.006	<0.007	0.034	0.050	-	0.033
Mo	0.98	1.07	0.94	0.95	0.52	0.71	-	0.55	0.10	0.06	0.17	0.16	0.64	0.69	0.41	0.47	0.52	0.65	-	0.54
Ni	39.9	28.5	36.3	36.4	0.37	0.85	-	0.45	0.58	0.44	0.42	0.45	0.36	0.95	0.30	0.34	0.38	0.85	-	0.46
Pb	50.5	29.7	28.6	33.5	0.73	0.13	-	0.63	0.90	0.74	0.44	0.54	<0.02	<0.02	0.17	0.17	0.41	0.14	-	0.36
Rb	119	117	123	122	64.7	144.7	-	78.6	15.9	49.1	13.6	15.5	13	44	12	13	34	91	-	44
Sb	2.01	1.58	2.06	2.03	0.033	0.008	-	0.029	0.0234	0.0095	0.0028	0.0070	<0.0006	<0.0006	<0.0006	<0.0007	0.016	0.005	-	0.014
Sn	4.81	4.56	4.15	4.32	<1.16	<0.06	-	0.94	<0.69	<0.06	<0.32	<0.38	<0.06	<0.06	<0.16	<0.14	<0.58	<0.06	-	<0.49
Sr	82	41	84	81	15.3	16.3	-	15.5	3.97	5.15	3.21	3.43	0.35	0.47	0.35	0.35	6.8	8.4	-	7.0
Th	17.5	19.2	15.3	16.0	0.0280	0.0008	-	0.0233	0.0140	0.0008	0.0061	0.0074	<0.0002	0.0009	<0.0002	<0.0002	0.013	0.001	-	0.011
Tl	0.60	0.59	0.66	0.64	0.014	0.144	-	0.037	0.0039	0.0029	0.0010	0.0016	<0.0002	<0.0002	<0.0002	<0.0002	0.006	0.067	-	0.017
U	3.74	4.53	4.45	4.30	0.0096	0.0042	-	0.0087	0.0062	0.0032	0.0025	0.0032	<0.0001	0.0006	<0.0001	<0.0001	0.0048	0.0026	-	0.0044
Zn	110	83	90	94	40.1	62.6	-	44	11.5	9.5	15.9	14.8	23.1	26.9	19.6	20.5	29	41	-	31
Zr	129	110	154	147	0.273	0.030	-	0.231	0.164	0.049	0.118	0.124	<0.013	<0.019	<0.007	<0.009	0.15	0.03	-	0.13

5.3.2. Element distribution in parts of rice plants

After being taken up primarily by the root apex and other parts of the root surface, ions are translocated by the xylem sap to the different plant parts. During the transport, many elements are enriched at cell walls (Greger 2004; Meharg and Zhao 2012). In general, the element transferability to plant parts depends on element species, plant genotypes/ cultivars, and external factors. The translocation of elements in the plant takes place by the phloem and/or xylem sap. Essential elements fulfill different biological functions such as osmoregulation and mass flow driven solute movement within the plant, stomata movement, energy transfer, controlling membrane permeability and electrochemical potentials. In addition, some of the elements serve as cell wall and membrane stabilizer and are necessary constituents of amino and nucleic acids, proteins, enzymes, coenzymes, and chlorophyll (Marschner 2012).

Average values for the plant parts and the aboveground plant are listed in Table 5.1. Element concentrations in plant parts and the aboveground rice plant are visualized in Fig. 5.1.

Average ratios of element concentrations of shoot to grain (Sh/Gr) and of husk to grain (Hu/Gr) are listed in Table A3.2. These ratios illustrate in which plant part the single elements are enriched or depleted. In decreasing order, the elements Ba, Na, Sr, Ca, Mn, Pb, Co, As, K, Cs, Cd, Fe, Rb, Ni, Mg, Zn, S, and Cu are more concentrated in the shoot than in unpolished grains (Sh/Gr 84 to 1). The elements Mo and P are easily transported and enriched in grains (Sh/Gr < 1), P even by factor 3. Concentrations of most elements (except Ni and P) are higher in shoot than in husk, especially Na, Cd, Mg, and K. Preferential transfer of some elements to grains may be explained by ion charges or the formation of organic complexes. Phosphate, molybdate and sulfate anions are repelled by the negatively charged cell walls allowing more distant transport (Marschner 2012). Copper, Zn, Mg, Ni and presumably some other metals are transported within the plant as soluble organic complexes facilitating their transport (Marschner 2012). The husk to grain ratio (Hu/Gr) shows no significant difference between the areas. Most elements show higher concentrations in husk compared to grain, except for Cu, Cd, S, Zn, P, Mg, and Mo.

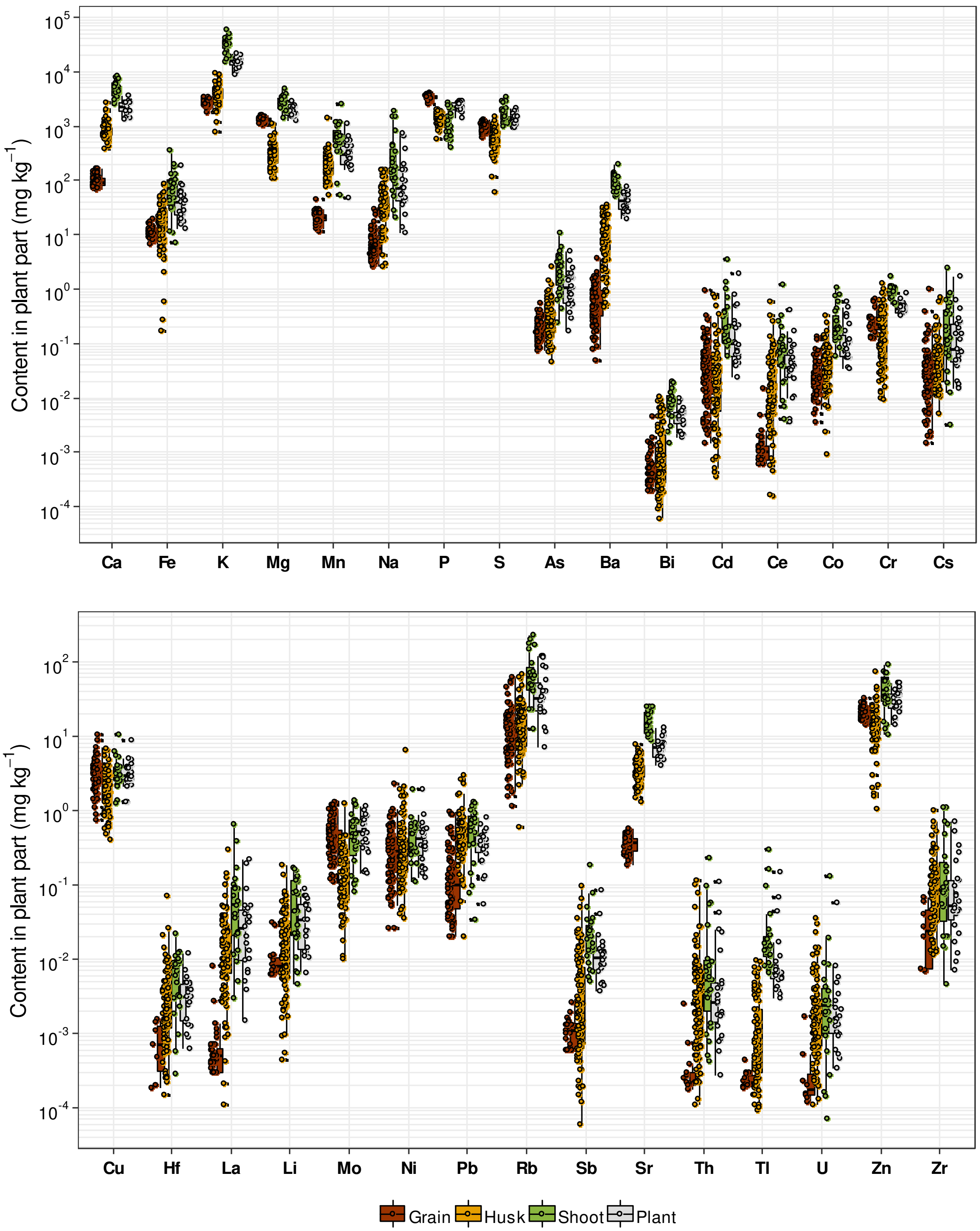

Fig. 5.1 Element concentrations in shoot, husk, grain, and whole aboveground rice plant (mg kg^{-1}) (shoot and plant: n = 23; husk and grain: n = 101). Concentrations of Bi, Ce, Cr, Hf, La, Li, Pb, Sb, Th, Tl, U, and Zr, whose concentrations are below detection limit in some grain samples limits are not plotted.

As a general trend, most element concentrations decrease in the order: shoot > husk > grain, while Cd, Mg, Zn, S, Cu, and Mo concentrations in shoot > grain > husk, and P concentration in grain > shoot > husk. Meng et al. (2018) found comparable results for the Cd distribution in rice plant parts.

Table 5.2 Average ratios of element concentrations in rice plant parts for the different areas

Ratio	Area	Ba	Na	Sr	Ca	Mn	Pb	Co	As	K	Cs	Cd	Fe	Rb	Ni	Mg	Zn	S	Cu	Mo	P
Sh/Gr	Red+Huong	84	71	42	37	30	-	15	12	12	11	9.1	7.4	4.7	2.7	2.0	1.8	1.6	1.3	0.9	0.3
Hu/Gr	Red+Huong	18	4.3	12	8.6	12	-	7.6	2.0	1.4	5.6	0.9	2.2	1.2	4.6	0.2	0.5	0.6	1.0	0.2	0.4
Hu/Gr	Mekong	14	6.9	9.4	8.7	8.4	5.7	2.1	1.8	1.6	3.1	0.9	2.0	1.2	1.9	0.3	0.8	0.7	0.7	0.5	0.4

Sh/Gr: Shoot/Grain; Hu/Gr: Husk/Grain. Concentrations of La, Tl, Ce, Th, U, Sb, Hf, Zr, Bi, Li, and Cr in grain are below detection limits.

To show the complexity of element transfer from roots to rice grains, some detailed investigations of other authors are summarized in the following. Seyfferth et al. (2011) detected on a root cross-section of a rice plant by using micro-X-ray absorption near-edge spectroscopy (µ-XANES), that Fe is distributed only along the xylem channel, whereas As, K, and Ca are present in the xylem and inside the cell vacuole. Zn and Mn are found only in vacuoles localized in the same area as K. The authors observed that mainly inorganic As(V) is enriched in the xylem and inorganic As(III) adjacent to the xylem channel. In addition, the total As uptake into rice plants is dependent on the extent of Fe plaques which are Fe-oxides/hydroxides coatings at the root surface (Moore et al. 2011), as well as by the type of cultivar and soil conditions (Eh, pH, concentration of As, soil phase composition). Additionally, As in grain can be delivered by phloem transport, where inorganic and organic As(V) forms are predominant (Ye et al. 2017). However, Ma et al. (2017) and Patel et al. (2016) determined a dominance of As(III) in rice grains. Seyfferth et al. (2011) as well delivered detailed element maps of a rice grain. They identified clear enrichments of Fe, As, K, Zn, Mn, and Ca in the bran relative to the interior part of the grain (endosperm). Furthermore, K, Ca, Mn, Zn, and Fe are enriched in the germ. Lombi et al. (2009) similarly proved by µ-XANES and PIXE that the bran is strongly enriched in P, K, Cu, Zn, and S. The germ within the grain accumulates more Zn, Mn, Cu, and Fe than the endosperm. Si and As are mainly located in the husk. Elevated concentrations of Mn, Fe, and Zn are scattered in some regions of the husk. According to Naito et al. (2015) the As concentration in brown rice drops by one third after polishing, confirming the As enrichment in the remaining bran.

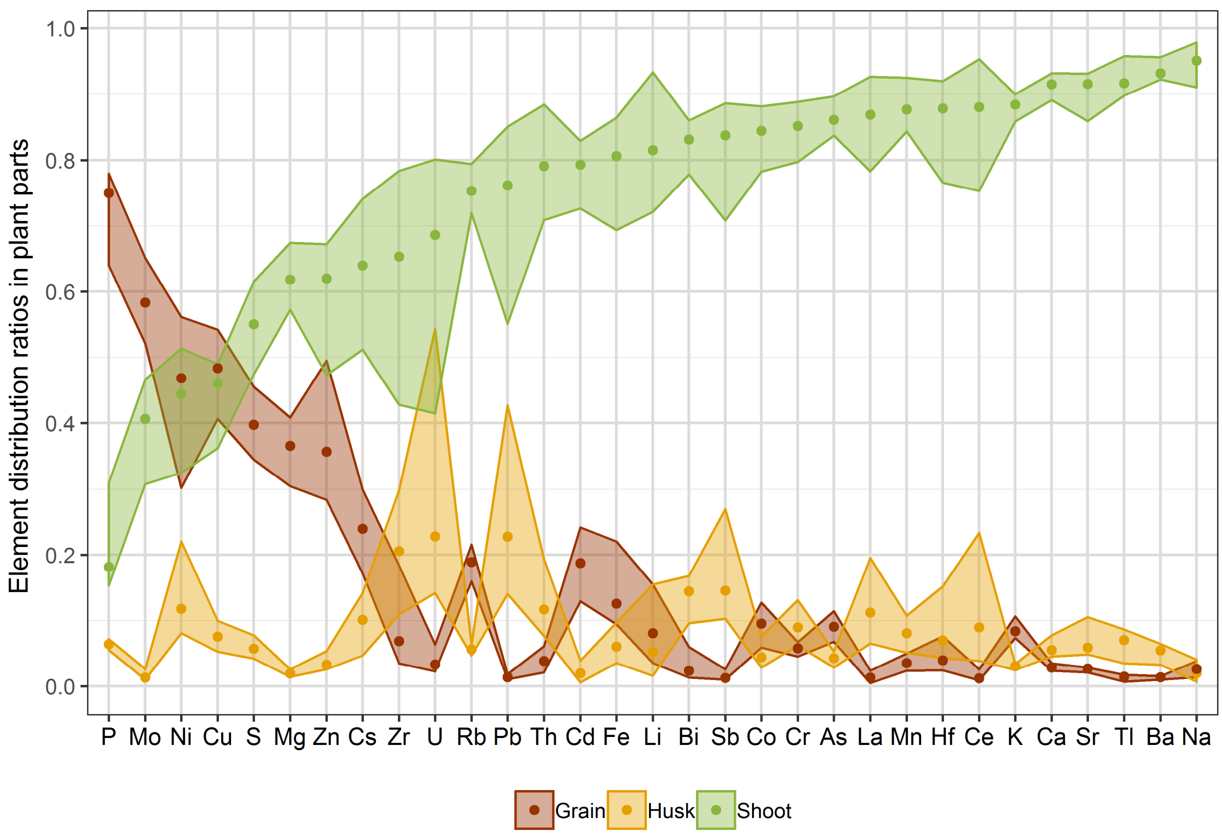

Fig. 5.2 Mass portions of elements in plant parts in relation to the aboveground rice plant. The sum of the portions of each element in grain, husk and shoot equals 1. Dots represent median values; the colored areas cover the range of the 1st to 3rd quartile portion for each element (n = 23)

The relative mass portions of elements in different parts of the aboveground rice plants is shown in Fig. 5.2. The mass portions of the plant parts in relation to the whole plant are on average 0.42 for shoot, 0.46 for grain, and 0.12 for husk (Table 5.1, detailed data in Table A3.1 in Appendix A3). More than 50% of the median amounts of most elements are stored in the shoot. In contrast, 50% - 80% of the amount of P, Mo, Ni, and Cu are stored in the grain. The storage of elements in husk is below 10% except for U, Pb, Zr, Bi, Sb, and La.

Mean concentrations of potentially harmful elements in soils and related rice plant parts from other regions in Asia are compared with results of this study in Table 5.3. Among the regions there are great differences in element concentrations, which may be attributed to different analytical techniques, especially during the digestion. We used total digestion releasing the elements completely into solution, whereas most of the other authors applied *aqua regia* or similar methods for soil samples. Arsenic concentrations in Japanese and Vietnamese soils are similar, but two times higher than in soils from India, Malaysia, Thailand, and China. However, husk and grain samples from India and Malaysia contain 2 - 3 times more As. This may be explainable by the very high As concentration up to 700 µg L^{-1} in the irrigation water (Biswas et al. 2013). Surprisingly, the As concentrations in shoots from India are about 3 times lower compared to China and Vietnam. The Cd concentrations in soils and grains from China, Japan, and Vietnam are remarkably higher than in other countries. Concentrations of other potentially harmful elements in grains are similar in China, Japan, and Vietnam. Grain samples from India and Malaysia have high contents of As, Cr and Pb. Korea shows remarkably low soil element concentrations compared to China, Japan, and Vietnam. Nearly all elements within the different areas show decreasing concentrations in the order soil > shoot > husk > grain.

Table 5.3 Mean concentrations of selected elements in soils and rice plant parts (mg kg^{-1}) in Vietnam compared to other Asian countries

	Country	Area	n	As	Cd	Cr	Cu	Mn	Ni	Pb	Zn
Soil	India	Nadia District, East coast	94	7.3	-	-	-	-	-	-	-
	Malaysia	Whole country	16	8.0	0.07	27	9	-	12	28	28
	Thailand	Whole country	108	6.4	0.04	25	12	-	13	20	24
	China	Yangtze River Delta	137	7.3	0.36	73	41	-	-	32	117
	Korea	Whole country	82	4.4	0.25		13		14	21	54
	Japan	North, east, center, south	10/111	14.0	0.45	-	20	-	-	-	96
	Vietnam	This work	101	14.4	0.29	87	33	343	36	33	93
Shoot	India	Nadia District, East coast	94/5	0.91	0.25	0.65	0.2	29	-	0.75	4.2
	China	Yangtze River Delta	137	3.51	0.34	0.83	26	-	-	1.97	63.8
	Vietnam	This work	101	2.82	0.44	0.92	3.5	723	0.45	0.63	44.0
Husk	India	Nadia District, East coast	94	0.74	-	-	-	-	-	-	-
	Japan	North, east, center, south	10	0.24	-	-	-	-	-	-	-
	Vietnam	This work	101	0.34	0.05	0.22	2.0	195	0.45	0.54	14.8
Grain	India	Nadia District, East coast	94/5	0.45	0.04	0.35	0.2	6.6	-	0.51	5.2
	Malaysia	Whole country	16	1.27	0.01	0.37	1.9	-	1.1	0.24	42
	Thailand	Whole country	108	<1	0.05	0.7	2	-	1.7	0.11	22.8
	China	Yangtze River Delta	137	0.13	0.06	0.19	5.2	-	-	0.10	22.8
	Korea	Whole country	82	0.15	0.02		4.3		0.35	0.11	22.6
	Japan	North, east, center, south	10/111	0.14	0.05	-	3.3	-	-	-	15.5
	Vietnam	This work	101	0.19	0.06	<0.24	3.3	21	0.42	0.17	20.5

India: Biswas et al. (2013) for As (n = 94) and Satpathy et al. (2014) for Cd, Cr, Cu, Mn, Pb, and Zn (n = 5); *Malaysia:* Zarcinas et al. 2004a; *Thailand:* Zarcinas et al. (2004b); *China:* Mao et al. (2019); *Korea*: Kunhikrishnan et al. (2015); *Japan:* Kuramata et al. (2010) for As (n = 10) and Herawati et al. (2000) for Cd, Cu, and Zn (n = 111)

5.3.3 Transfer factors soil to rice plant

In this study, transfer factors (TF) from soil to aboveground plant are calculated as ratio of physiological plant concentration to soil concentration for the Red River and Huong River areas. The TFs for grains have been discussed in two previous publications (Nguyen et al. 2019a, b). The TFs of shoot and husk are not considered in detail here because their trends are similar to the concentration trends described in the preceding chapter.

According to Table 5.4 and Fig. 5.3, the median TF-values of elements for the aboveground plant decrease in the order:

- Very low transfer (TF <0.001): Ti, Al, Th, U, Ce, Zr, La, Li, Hf, Fe
- Low transfer (0.001 – 0.01): Co, Sb, Bi, Pb, Ni, Sn
- Intermediate transfer (0.01 – 0.1): Tl, Na, Cs, As, Cu, Sr
- High transfer (0.1 – 1): Ba, Mg, Rb, Zn, Cd, Ca, Mn, Mo, K
- Very high transfer (>1): P, S

The TFs for elements vary by many orders of magnitude. The lowest TF is around 0.00001 for Th and even lower for elements whose concentrations are below detection limit while the highest TF is 7.2 for S. Even the transferability of a single element shows wide variations: For example, the TFs of Th and Cs vary by factor 240, Na by factor 204. Such variations reflect the sensibility of the element phytoavailability under differing soil conditions. Some elements like Ca, K, Mg, P, Ba, Cr, Pb, Sr, and Zn have a more stable uptake with TF fluctuating by less than factor 10. Notably, the TF of As and Cd fluctuates 78- and 115-times respectively, showing a potential to govern their uptake by changing the soil conditions such as pH or Eh. Another reason for such fluctuations may be different uptake patterns of various rice cultivars, as described for Cd and As by Duan et al. (2017), Chi et al. (2018), Islam et al. (2016), Liu et al. (2011), and Li et al. (2017). The rice cultivars of this study, however, were not distinguished during the sample collection.

Table 5.4 Average transfer factors for elements in shoot, husk, grain, and in the whole aboveground rice plant in the three different river areas

Ele-ment	**Shoot** (n = 23)				**Husk** (n = 101)				**Grain** (n = 101)				**Plant** (n = 23)			
	Red	Huong	Mekong	Mean	Red	Huong	Mekong	Mean	Red	Huong	Mekong	Mean	Red	Huong	Mekong	Mean
Al	<0.00005	<0.00005	-	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	-	<0.00005
Ca	1.06	1.80	-	1.19	0.23	0.65	0.21	0.23	0.029	0.064	0.025	0.027	0.48	0.96	-	0.56
Fe	0.002	0.005	-	0.002	0.0006	0.0008	0.0006	0.0006	0.0003	0.0004	0.0003	0.0003	0.001	0.003	-	0.0012
K	1.92	1.16	-	1.79	0.22	0.27	0.20	0.21	0.16	0.15	0.13	0.14	0.87	0.64	-	0.83
Mg	0.40	0.55	-	0.42	0.04	0.07	0.05	0.05	0.20	0.22	0.20	0.20	0.26	0.36	-	0.28
Mn	1.88	3.36	-	2.14	0.54	1.02	0.75	0.73	0.05	0.09	0.09	0.08	0.87	1.73	-	1.02
Na	0.09	0.17	-	0.11	0.005	0.003	0.012	0.010	0.001	0.002	0.002	0.002	0.04	0.08	-	0.047
P	1.46	2.97	-	1.72	1.63	2.32	1.94	1.89	4.4	6.7	4.5	4.6	2.8	4.6	-	3.14
S	4.10	6.31	-	4.48	1.86	1.38	0.95	1.14	2.9	2.6	1.4	1.7	3.3	4.2	-	3.46
Ti	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As	0.14	0.25	-	0.16	0.022	0.057	0.024	0.025	0.007	0.020	0.015	0.014	0.06	0.13	-	0.08
Ba	0.25	0.28	-	0.25	0.06	0.05	0.02	0.026	0.0033	0.0033	0.0013	0.0017	0.11	0.14	-	0.11
Bi	0.017	0.014	-	0.016	0.010	0.006	0.002	0.003	<0.0005	0.0026	<0.001	<0.001	0.008	0.008	-	0.008
Cd	1.31	1.98	-	1.43	0.30	0.71	0.11	0.171	0.361	0.373	0.151	0.200	0.76	1.12	-	0.82
Ce	0.0015	0.0027	-	0.0017	0.0010	0.0006	0.0003	0.0004	<0.00001	0.00006	<0.00001	<0.00001	0.0007	0.0013	-	0.0008
Co	0.013	0.061	-	0.021	0.0054	0.0108	0.0037	0.004	0.0011	0.0069	0.0021	0.0021	0.006	0.033	-	0.011
Cr	0.016	0.019	-	0.016	0.0058	0.0107	0.0019	0.003	<0.001	<0.001	<0.002	<0.003	0.007	0.011	-	0.008
Cs	0.03	0.20	-	0.06	0.0187	0.0743	0.0036	0.009	0.007	0.080	0.003	0.0065	0.018	0.136	-	0.038
Cu	0.08	0.14	-	0.09	0.052	0.082	0.068	0.065	0.08	0.14	0.11	0.11	0.074	0.136	-	0.09
Hf	0.0016	0.0022	-	0.0017	0.0013	0.0006	0.0010	0.0011	<0.00008	<0.00014	<0.00005	<0.00005	0.0008	0.0012	-	0.0009
La	0.0023	0.0026	-	0.0024	0.0011	0.0007	0.0004	0.0005	<0.00001	0.00007	<0.00001	<0.00001	0.0010	0.0013	-	0.0011
Li	0.002	0.004	-	0.0023	0.0008	0.0008	0.0005	0.0006	<0.0001	<0.0005	<0.0001	<0.0001	0.001	0.002	-	0.0012
Mo	0.82	0.74	-	0.81	0.12	0.06	0.21	0.19	0.98	0.72	0.49	0.59	0.80	0.67	-	0.78
Ni	0.010	0.035	-	0.015	0.016	0.017	0.012	0.013	0.010	0.039	0.009	0.010	0.011	0.035	-	0.015
Pb	0.016	0.005	-	0.014	0.021	0.023	0.016	0.017	<0.0005	<0.0005	0.0063	<0.005	0.009	0.005	-	0.008
Rb	0.68	1.32	-	0.79	0.176	0.452	0.114	0.139	0.15	0.41	0.10	0.12	0.36	0.84	-	0.45
Sb	0.023	0.005	-	0.02	0.015	0.006	0.001	0.0042	<0.0003	<0.0003	<0.0003	<0.0003	0.011	0.003	-	0.0095
Sn	<0.01	<0.23	-	<0.19	<0.13	<0.01	<0.08	<0.09	<0.01	<0.01	<0.04	<0.03	<0.12	<0.01	-	<0.097
Sr	0.23	0.41	-	0.26	0.06	0.13	0.04	0.046	0.005	0.012	0.004	0.005	0.10238	0.21050	-	0.12
Th	0.00151	0.00005	-	0.0013	0.00077	0.00004	0.00040	0.0005	<0.00001	0.00004	<0.00001	<0.00001	0.00069	0.00004	-	0.0006
Tl	0.03	0.27	-	0.069	0.007	0.005	0.001	0.003	<0.0003	<0.0003	<0.0003	<0.0003	0.012	0.127	-	0.032
U	0.003	0.001	-	0.002	0.0017	0.0007	0.0006	0.0008	<0.00002	0.00013	<0.00002	<0.00002	0.0013	0.0006	-	0.0011
Zn	0.39	0.75	-	0.45	0.12	0.12	0.19	0.17	0.22	0.33	0.23	0.23	0.28	0.50	-	0.31
Zr	0.0020	0.0003	-	0.0017	0.0017	0.0005	0.0008	0.0009	<0.00005	<0.00018	<0.00005	<0.00004	0.0011	0.0003	-	0.0010

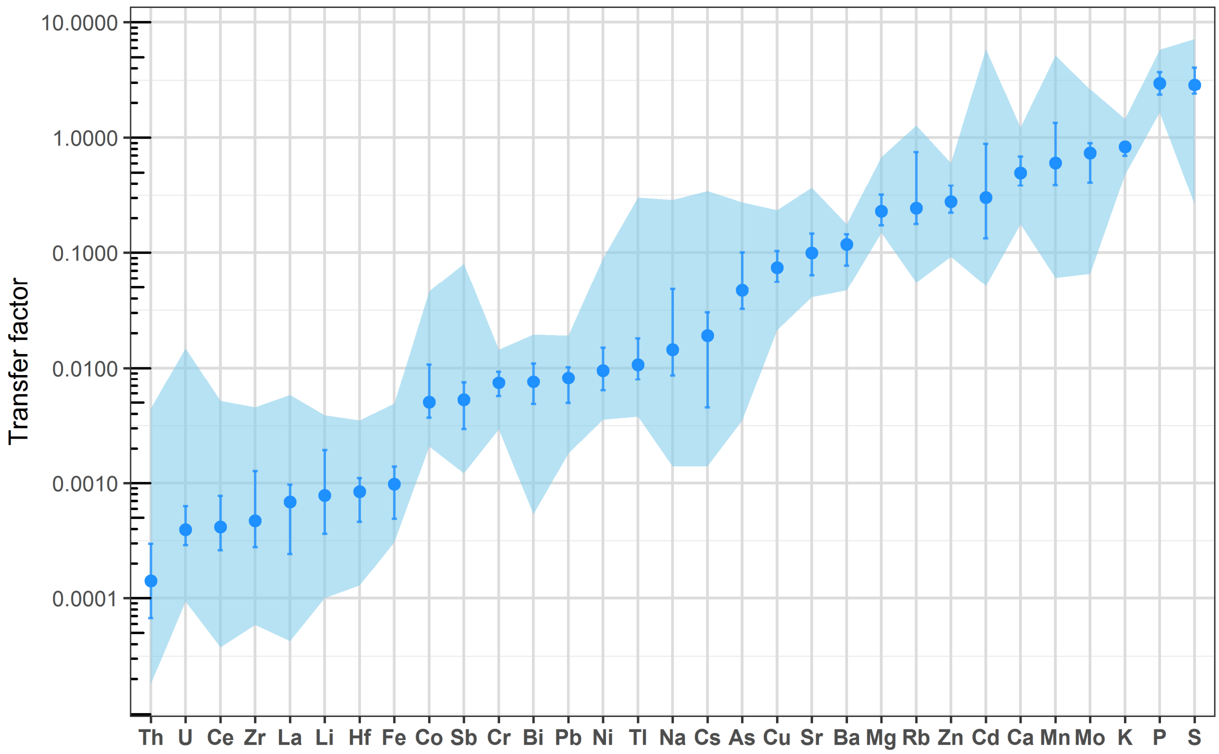

Fig. 5.3 Transfer factors from soil to aboveground plant for the Red River and Huong River area (n = 23). Dots are median values. The straight line indicates the 1st to 3rd quartile of the TFs. The colored zone marks the area between minimum and maximum values.

Soil parameters that determine the transferability for each element from soil to the aboveground plant are presented in Table 5.5. The uptake of elements is simultaneously influenced by their concentration and speciation in the soil solution, which depend on redox- and pH-value, the concentration and reactivity of sorbents (Fe and Mn oxides/hydroxides, clay minerals and organic matter), and microbial activities. The influence of the soil concentration of each element and of the soil parameters pH, OM, Al, Fe, and Mn on the TFs is evaluated on the basis of xy-scatterplots in Fig. A3.2 and Fig. A3.5 (Appendix A3). It was not possible to measure Eh-values and microbial activities in the field.

The TFs of the elements Ca, Mg, Mn, Na, P, S, As, Bi, Cr, Cs, Cu, Mo, Ni, Pb, Rb, Sb, Sr, and Zn decrease exponentially with their increasing soil concentrations (Table 5.5; Fig. A3.2 in the supplementary material). However, these elements show no significant correlation between soil and plant concentrations. Increasing soil element concentrations systematically lower the TFs demonstrating that the decrease of TF is a spurious effect.

Table 5.5 Influences of soil parameters and soil element concentrations and pH-value on transfer factors (TF) for aboveground rice plants from the Red River and Huong River areas

TF	**Soil factors**	TF	**Soil factors**
Ca	-Ca, -pH > -Mn > +Al	Cs	-Cs
Mg	-Mg, -Fe > -Mn	Cu	-Cu > -LOI > -pH
Mn	-Mn > -pH	Mo	-Mo > -Fe, -Al, -LOI, +pH
Na	-Na, +Fe > +LOI > +Al	Ni	-Ni > -Mn, -pH, -Fe
P	-P > -pH > -Mn	Pb	-Pb
S	-LOI, -S > -Al, -Fe	Rb	-Rb > -Fe, -Al
As	-As > +LOI , -Fe,	Sb	-Sb > +pH, -Fe
Bi	-Bi > -Fe	Sr	-Sr > -Fe > -pH
Cd	-pH > -Mn	Tl	-pH, -Mn
Co	-pH, -Mn	Zn	-Fe, -Zn
Cr	-Cr, -Fe > -Al, -LOI		

"+" positive correlation trends (mostly linear); "-" negative correlation trends (mostly exponentially decreasing); Fe, K, Ba, Li, Sn, and U show no visible correlation with soil factors or their soil concentration.

The influence of the soil parameters pH, LOI, Al, Fe, and Mn on the TF of an element is in general less relevant than its soil concentration (Table 5.5 and Fig. A3.5 in Appendix A). This is easily explainable by the fact that each soil parameter has a different impact on element availability. Thus, the element concentration in the plant reflects the combined effects of all soil parameters as mentioned in literature (Blume et al. 2016). Some effects of soil parameters on the TFs are summarized here:

- The negative correlation trends of the TFs of elements Ca, Mn, P, Cd, Co, Cu, Ni, Sr, and Tl with soil pH-value may be explained by higher plant-available element concentration in soil solution at lower pH-value. In an acidic environment, H^+ ions can replace sorbed cations at the surfaces of soil phases and release them into solution. This facilitates the element uptake by the plant. In circum-neutral soils, these elements are much less soluble. Compared to the other elements, Cd, Co, and Tl show an extremely sharp decrease of their TF at low pH-value. An additional reason for the negative trends between pH-value and TF for the elements Ca, Mn, P, Cd, Cu, and Sr is again a spurious effect: Their concentration increase in the soil with rising pH lowers their TFs.
- Opposite to cations, Mo shows an increased uptake trend towards higher pH-value. Under reducing conditions Mo is able to form complexes with organic matter, presumably with sulphur-groups. Increasing soil pH-values lead to more biological destruction of organic matter releasing Mo into the soil solution.

- The TFs of Cr and Mo are negatively correlated with soil Fe and Al. Chromium and Mo are less sorbed at low Fe and Al soil concentrations facilitating their plant uptake.
- The positive correlations between the TFs of As, Bi, and Sb suggest their similar solution behavior in the soil and comparable uptake mechanisms by the plant.
- The TFs of Mg, S, As, Bi, Cr, Mo, Ni, Rb, Sb, Sr, and Zn show negative trends with the soil concentrations of Fe and Al. The sorption of these elements on Fe-oxides/hydroxides or clay minerals leads to their decreased bioavailable concentrations in soil solution and hence in rice plants. In contrast, the TF of Ca correlates positively with soil concentrations of Al and Fe. Their phases hold mobile Ca and Na cations available to plants.
- The TFs of Ca, Mg, Mn, P, Cd, Co, Ni, and Tl decrease exponentially with increasing Mn-concentrations in the soils. A smart explanation may result from the positive correlation of the soil Mn concentration with increasing soil-pH leading to a spurious negative trend between soil Mn concentration and the TFs of the elements.
- The LOI concentration influences positively the TF of As. The organic matter may form soluble As-organic complexes facilitating the As-transport into the plant. In contrast, increasing LOI concentrations in the soil lead to decreasing TFs of S, Cr, Cu, and Mo. Sulphur is compound of the OM, the other elements may be sorbed. At oxidizing conditions and/or at higher pH-value, organic compounds are degraded and release these elements into solution facilitating their plant uptake.

5.3.4 Health risk assessment

Potentially harmful elements such as As, Cd, Pb, Co, Cu, Mn, Mo, and Ni are selected to estimate the non-cancer risk by means of Target Hazard Quotients (THQ) for an elements and chronic cumulative Hazard Index (HI) for all selected elements (USEPA 1989; Nordberg et al. 2015a). Elements with implicit carcinogenic risk like As and Pb are evaluated by means of Incremental Lifetime Cancer Risk (ILCR) and Cumulative Cancer Risk (∑ILCR). Statistics on the exposure risk of single elements and total health risks are compiled in Table 6 for the three river areas (detailed data in Table A3.6 in Appendix A3). The HI and ∑ILCR for the single samples of the three river areas are plotted in Fig. 5.4.

Table 5.6 Indexes for health risk assessment for potentially harmful elements including non-cancer risk and cancer risk

Index	Area	Statistics	As	Pb	Cd	Co	Cu	Mn	Mo	Ni	HI	∑ILCR
RfD (x10^{-3})			2	1.5	1.5	0.35	200	200	40	20		
CDI	Red	Min-Max	0.8-2.6	<0.2	0.02-7.4	0.03-0.24	5.5-65	88-348	1.4-9.9	0.2-7.8		
(x10^{-3})		Mean	1.6	<0.2	0.92	0.12	26	170	4.9	2.8		
	Huong	Min-Max	1.0-2.6	<0.2	0.33-0.96	0.48-1.02	21-36	163-202	3.7-7.0	2.9-17		
		Mean	2.1	<0.2	0.63	0.63	27	181	5.3	7.3		
	Mekong	Min-Max	0.6-4.3	0.02-7.1	0.06-0.88	0.06-0.88	8.4-78	101-219	0.8-7.8	0.2-23		
		Mean	1.4	1.3	0.19	0.19	25	158	3.2	3.1		
	Mean	Mean	1.5	1.0	0.42	0.20	25	161	3.6	3.2		
THQ	Red	Min-Max	0.41-1.3	<0.1	0.05-21	0.02-0.16	0.03-0.33	0.44-1.74	0.03-0.25	0.01-039	1.4-24	
		Mean	0.80	<0.1	2.6	0.08	0.13	0.85	0.12	0.14	4.7	
	Huong	Min-Max	0.5-1.3	<0.1	0.93-2.7	0.32-0.68	0.11-0.18	0.81-1.01	0.09-0.18	0.15-0.86	3.7-6.1	
		Mean	1.04	<0.1	1.86	0.42	0.14	0.91	0.13	0.37	4.9	
	Mekong	Min-Max	0.29-2.1	0.1-4.7	0.03-4.1	0.04-0.59	0.04-0.39	0.50-1.09	0.02-0.20	0.01-1.13	1.6-8.4	
		Mean	0.70	0.87	0.81	0.13	0.12	0.79	0.08	0.15	3.7	
	Mean	Mean	0.73	0.69	1.19	0.13	0.13	0.81	0.09	0.16	3.9	
ILCR	Red	Min-Max	1.2-3.9	<0.001								1.2-3.9
(x10^{-3})		Mean	2.4	<0.001								2.4
	Huong	Min-Max	1.5-3.9	<0.001								1.5-3.9
		Mean	3.1	<0.001								3.1
	Mekong	Min-Max	0.9-6.4	0.001-0.06								0.9-6.4
		Mean	2.1	0.01								2.1
	Mean	Mean	2.2	0.009								2.2

RfD: the reference dose of an element represents its maximum permissible level for daily intake per kg human body weight in mg kg^{-1} b.w. day^{-1} (recalculated data from Nguyen et al.2019a); *CDI*: Chronic Daily Intake of an element from rice consumption in mg kg^{-1} b.w. day^{-1}; *THQ:* Target Hazard Quotients; *HI:* chronic cumulative Hazard Index for non-cancer risk; *ILCR:* Incremental Lifetime Cancer Risk; ∑*ILCR:* Incremental Cumulative Cancer Risk

Non-cancer risks

Chronic cumulative Hazard Indexes (HI) for the intake of the elements As, Cd, Pb, Co, Cu, Mn, Mo, and Ni from rice consumption are calculated. All samples have HI values ≥ 1.4 surpassing the safe level of 1 as suggested by USEPA (1989). 39% of the samples show HI-values between 1.4 and 3, 44% between 3 and 5, and 18% between 5 and 8.4. Rice consumption poses health hazards of concern with HI > 5 in 26% of the Red River samples, in 2 of 4 samples from the Huong River, and 14% of the Mekong River samples. Cadmium, As, Pb, and Mn are the most prominent harmful elements by rice consumption and contribute 64 - 97% (average 86%) to the HI. In some samples, the THQs of Cd, Pb, As, and Mn are very high, reaching 21, 4.7, 2.1, and 1.7 respectively. The elements Ni, Cu, Co, and Mo are present a much lower risk. Other sources for harmful element intake such as other food, drinking water or air pollution are not considered in this study.

For arsenic, 3 of 4 samples from the Huong River, 26% of the Red River samples and 14% of the Mekong River samples have THQ_{As} > 1. Arsenic contributes on the average 22% to the HI value in the three river areas. For cadmium, 39% of the Red River and 29% and

Mekong River samples show $THQ_{Cd} > 1$. Especially, samples HN10 and HN9, collected close to a brick manufactory, have THQ_{Cd} of 21 and 7 respectively. Cadmium contributes on the average 23% to the total hazard index (HI) in the three river areas. All of the Red River and Huong River grain samples have very low Pb concentrations < 0.02 mg kg^{-1} corresponding to CDI_{Pb} < 0.2 mg kg^{-1} b.w. day^{-1} and $THQ_{Pb} < 0.1$. Lead is just responsible for less than 2% of the HI-value in these two river areas. In contrast, the Mekong River grain samples contain at least 10-times more Pb than the samples from the other rivers. Lead contributes 3 - 69% (average 21%) to the total hazard risk in the Mekong River area. Manganese is usually not considered as a harmful element. In fact, Mn, on the average, holds 24% of the HI value, being the highest contributor compared to the other harmful elements. Manganese surpasses THQ = 1 in 10% of the samples, but 99% of the samples have THQ > 0.5.

For a better understanding of the HI value, the following aspects should be considered: If the calculation of HI would be performed with the reference doses RfD of the 8 elements listed in Table 5.6, the HI value would be 8. Because of their nutrient character Ca, Mg, P, Fe, and Zn are not included in our list although their RfD values are available. Magnesium alone would increase the HI by at least 1. In so doing, an increasing number of potentially harmful substances in the rice grain boost the values of HI, but also the values ∑ILCR. In case Mg would be included additionally, many of the samples would be located in the very high risk field of HI > 5. In addition, the positive health effects of the beneficial elements Cu, Mo, Mg, and Mn are not considered in the schematic addition assessment applied here. Furthermore, antagonistic and synergistic effects are neglected, because studies of interactions among toxic elements in human body are limited (Nordberg et al. 2015b).

Cancer risk

The index of Incremental Lifetime Cancer Risk (ILCR) for As and Pb from rice consumption, as well as the Cumulative Cancer Risk (∑ILCR) is calculated and shown in Table 6 and Fig. 5. All samples exceed the threshold of acceptable cancer risk which should be between 10^{-4} to 10^{-6} according to USEPA (1989). At the ∑ILCR between 10^{-4} and 10^{-3}, health risk management should take action. The ∑ILCR values fluctuate from 0.9 x 10^{-3} to 6.4 x 10^{-3} (average 2.2 x 10^{-3}) revealing a high level of cancer risk. The mean risk levels ∑ILCR are 2.1 x 10^{-3} for the Mekong River rice, 2.4 x 10^{-3} for the Red River rice, and 3.1 x 10^{-3} for the Huong River rice. The slightly greater risk of the Huong River samples might be due to the strongly acidic condition there (Nguyen et al. 2019a). Of these two elements, As contributes to 96% of

∑ILCR while Pb only holds 4% of the cancer risk. Cadmium is another important cancer risk factor for Red River and Huong River rice. However, the missing reliable data for food intake makes it impossible to consider Cd in this research.

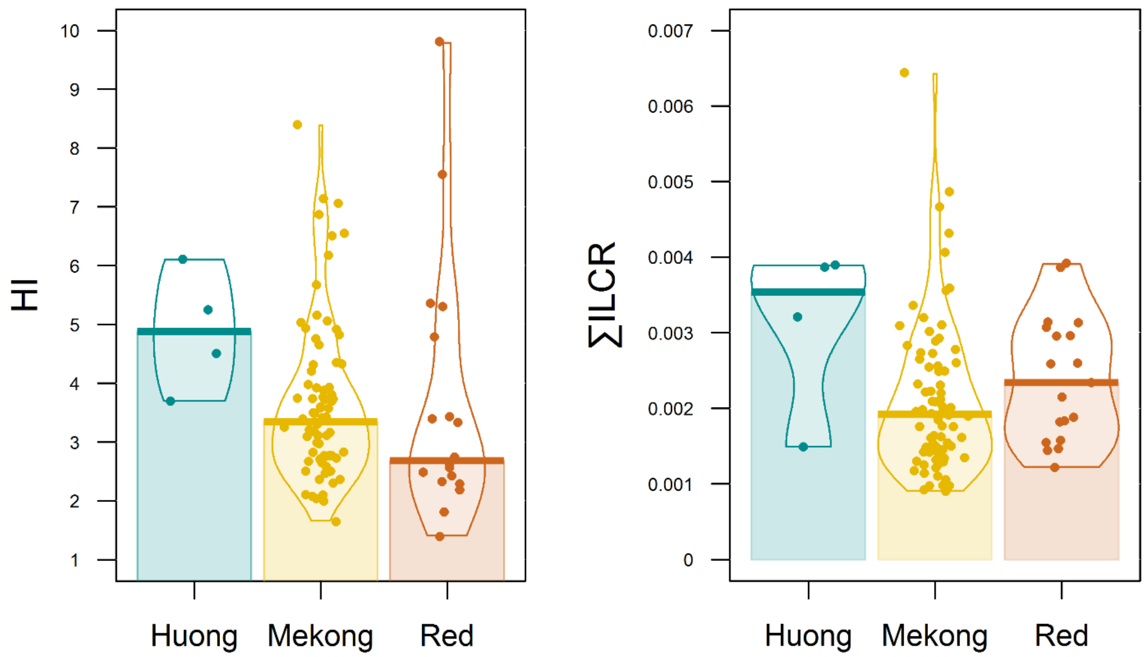

Fig. 5.4 Target hazard index (HI) for non-cancer risk from intake of As, Cd, Pb, Co, Cu, Mn, Mo, and Ni by rice consumption and cumulative carcinogenic risk (∑ILCR) from As and Pb intake. The horizontal lines represent the medians. The extreme HI-value 24 of sample HN10 from the Red River area is not plotted.

Both cancer risks and non-cancer risks from rice consumption are considerably higher than the tolerable health risks. Our results show the urgent need to lower the uptake of potentially harmful elements into rice grains. In addition to the critical comments given above, the indexes may deliver only rough risk estimates for several reasons: The simple addition of single elements quotients to get the health risk seems questionable because of lacking knowledge about the interaction among the elements and other harmful compounds (Nordberg et al. 2015a). In addition, more sources of harmful elements such as other food, drinking water, air pollution, etc. additionally aggravate the situation. All calculations in this paper are done for adult lifetime exposure without considering the special stages of infancy, child, and old age. According to Liao et al. (2018), these sensible age groups may have an elevated cancer risk even with lower rice consumption, because the cancer slope factor for these groups are higher. The evaluation system used here is not appropriate to get an exact risk calculation, because some health-relevant elements are not included. However, the system helps to get a relative risk contribution of every harmful substance and allows to compare the risk for different rice samples. Altogether, at least the elements As, Cd, Mn, and Pb should be investigated as basis for risk assessment studies. Especially for these elements further possibilities to lower their uptake by rice grains should be explored.

5.4 Conclusion

101 paddy soil and rice plant samples were collected in the Red River Delta in northern, Huong River area in the center, and Mekong River Delta in southern Vietnam. The soils contain comparable alluvial parent materials, verified by similar main, minor and trace element concentrations. However, soil parameters like Eh/pH-values, concentrations of sorbents such as organic matter, Fe-oxides/hydroxides and clay minerals can lead to great differences of element transferability into rice plants. Huong River soils are acidic (pH = 4.2 - 4.7), Mekong River soils are acidic to nearly neutral (pH = 3.7 - 6.8), and Red River soils are mostly circum-neutral (pH = 4.8 - 7.3). Mekong River soils contain a higher concentrations of organic matter (10.3%) compared to Red River soils (6.5%) and Huong River soils (6.4%). Soluble organic complexes are suggested to be responsible for the high Pb concentration (average 0.17 mg kg^{-1}), especially in Mekong River grains. The application of large amounts of phosphate fertilizers might be a reason of the high Cd concentration in Red River grains (average 0.116 mg kg^{-1}). The As concentrations in Huong River grains (average 0.27 mg kg^{-1}) are possibly caused by stronger dissolution of Fe-oxides/hydroxides as the main sorbents for As at low soil pH-values.

Elements are transported within the plant through the xylem and phloem sap. During this process, cations interact with negatively charged cell walls decreasing their transfer rate on their way from root to grain. For this reason, concentrations of most elements gradually decrease with increasing distance from the root in the order: shoot > husk > grain. Exceptions are Cd, Mg, Zn, S, Cu, and Mo, whose concentrations decrease in the order: shoot > grain > husk. In particular, the P concentration decreases in the order grain > shoot > husk. The preferential transfer of S, Mo, and P into the grain is probably due to their anionic character and their electrostatic repulsion at negative loaded cell walls. The transport of Cu, Zn and Ni into the grains may be facilitated by the formation of soluble organic complexes in the sap.

Health risk calculations on basis of the daily intake of As, Cd, Pb, Cu, Mn, Mo, and Ni by rice consumption indicate, that all unpolished rice grains are within unsafe levels of non-cancer risk with chronic cumulative Hazard Indexes (HI) between 1.4 and 8.4 (one sample even reaching 21). The risk level HI = 1 should not be exceeded. 18% of all samples surpass the high risk level of HI = 5 in Huong River area 2 out of 4, Red River area 26%, and the Mekong River area 14%. The elements Cd, As, Mn, and Pb are main contributors to the HI-value covering 64 - 97% of the HI (average 86%). These elements should be included into any health risk study for rice consumption. Further possibilities to lower their uptake by rice grains should be explored.

The cancer risk index (∑ILCR) of As and Pb fluctuates from 0.9 x 10^{-3} to 6.4 x 10^{-3} (mean 2.2 x 10^{-3}). It is considerably higher than the acceptable cancer risk threshold of 10^{-4} and 10^{-6}. Mean ∑LCR-values are 2.1 x 10^{-3} for Mekong River grain, 2.4 x 10^{-3} for Red River grain, and 3.1 x 10^{-3} for Huong River grain. Arsenic is the most potential carcinogenic risk factor for Vietnam rice.

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5.6 Supplementary material

The supplementary material is presented in Appendix A3

5.7 References

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Chapter 6

General conclusions and perspectives

General conclusions and perspectives

110 soil samples and corresponding rice grain samples in the Mekong River, Red River, and Huong River area in Vietnam were analyzed for main and ultratrace elements to get information about the concentration, the soil-plant transfer of elements, enrichment of potentially harmful element and related health risks for the population. In addition, the husk and the aboveground rice plant collected in the Red River and Huong River area were also analyzed. The translocation of nutrient and harmful elements from soil into rice plants under varying soil conditions were discussed. This knowledge is a basis for understanding and helping limiting the uptake of harmful elements by rice. It is obvious that in some areas in Vietnam with increased burden of toxic elements in rice grains, the large consumption of local rice may cause chronic potential health risks for the population. The goals of this work are to contribute to a better comprehensive and systematic understanding of how the soil compositions determine the transfer of elements into rice.

6.1 General conclusion

Soil geochemistry

The paddy soils in the three river areas consist mainly of alluvial sediments, which consist of eroded materials transported by the rivers. Beside material from the surrounding mountains, the Red River contains suspended load from the Yunnan Plateau, the Mekong from the Tibetan Plateau, the Huong River from the Annamite Range of eastern Indochina Vietnam. Because geochemical data for these suspensions are not available, the main and trace element concentrations of the investigated paddy soils are compared with world-wide average concentration values of the upper earth crust and/or global shale data as proxies for the parent material. This comparison helps to decipher if the soils are contaminated by anthropogenic sources or if elements are lost by weathering. The following depletion or enrichment trends can be stated for the investigated paddy soils in Vietnam (n = 110):

- Depleted element (decreasing depletion): Ca, S, Mg, Ni, Li, Sr, Mn, Na, K, Mo, Cr, Ba, Hf, Co, V, Zr, Fe, Sb
- Elements with changes of less than 10 %: Cu, Tl, Sc, Rb, Al, Ga, Ti, Si
- Enriched elements (increasing enrichment): P, Ce, Cs, Th, U, La, Nb, Sn, Pb, As, Cd, Bi.

The paddy soils in three river areas have similar compositions, showing that the parent materials are comparable. There are, however, some distinguishable discrepancies in soil pH and OM content among the areas. The Huong River soils are acidic (mean pH = 4.4), the Mekong River soils weakly acidic (mean pH = 5.0), and Red River soils close to neutral (mean pH = 6.2). The soils in Mekong River have much higher OM contents (mean LOI 10.3%) than Red River and Huong River soils (mean LOI 6.5%).

In comparison with the average shale or upper Earth crust, elements such as Ce, Th, As, La, U, Sn, Cs, and Bi are naturally enriched in the paddy soils. The slight enrichment of P, Cd, and Pb can be attributed to fertilizer and emission inputs. However, nearly all of the potentially harmful elements are in the allowable levels of Vietnamese agricultural soil, except for As. 92 % of the Red River soils, 20 % of the Huong River soils, and 11 % of the Mekong River soils exceed the Vietnamese permissible As limit of 15 mg kg^{-1}. The average As concentration in the Red River soils is 22.5 mg kg^{-1}, remarkably higher than those in Huong River soils (13.5 mg kg^{-1}) and in Mekong River soils (12.6 mg kg^{-1}). The obviously high As concentrations are probably delivered by the transported-river materials in combination with reducing processes in the rice fields. One possible enrichment mechanism may be: in the deeper reducing soil layer, As may be released in solution and subsequently be diffused into upper parts of the soil profile, where it may be enriched under the intermittent reducing and oxidizing conditions. Only a few of the investigated paddy soils show clear signs of strong anthropogenic contamination. Paddy soils close to a Lam Thao fertilizer and chemical factory in the Red River are polluted by factory effluents, delivering the dangerous elements As, Cd, Cu, Pb, Zn, Co, Mo, U, S, Cr, (and Fe). Two sites collected in the Red River bank are enriched in As, Bi, Cd, Cu, Mn, Pb, Sb, Sn, Zn, and rare-earth elements such as La and Ce. Reason for their enrichment may be the expoitation of the Adebo monazite ($Ce[PO_4]$) mine in Jinping, the Yuanjiang Gold Mine, Grjiu Tin Mine, and Laojinshan Gold Mine in Yunnan Province, China.

Mainly highly significant positive correlations between the elements can be observed within the following groups: group 1 – Ba, Ti, Th, K, Rb, Tl, Ga, V, Al, Sc, Cs, Fe, Mg, Nb, Ce, and La (elements contained in silicates without quartz); group 2 – Hf and Zr (contained in the mineral zircon; both are immobile elements with identical loading and ionic diameter); group 3 – Ca, P, Na, and Sr (fertilizer group); group 4 – organic matter (OM) and S (OM is the main host for S as part of the OM or as sulfide associated with OM). The main reason for the mostly highly significant positive correlation coefficients within the four groups is the varying amount of quartz and/or bio-opal in the soil samples. Increasing concentrations of these phases dilute the elements within the groups and cause spurious correlations.

The concentrations of trace elements in the paddy soils can be related to the the main soil phases: pH, OM, Al-, Fe-, and Mn-phases, which govern the binding, sorption, and coprecipitation of trace elements in soil and thus impact the trace element phytoavailability. Multiple regression analysis between these main soil factors and trace element concentration shows the visible associations as follows: Fe-phases: Co, As, Cd, and Sb; Al-phases: Tl, V, Bi, Sn, Pb, U, Ni, Zn, Cu; and OM: Mo and S. It must be taken into account that the soil parameters also mutually interact. For example, soil pH affects the formation or dissolution of Fe-, Al-, and Mn-phases, and the microbial oxidation of OM. The influence of the changing redox conditions could not be included into the calculations, because the Eh values are highly variable during the growing season and could not be measured continuously.

Transferability and distribution of elements into rice plant

After taken up by root, osmoregulation and mass flux drive the translocation of elements within the rice plant. The flow rate and composition of xylem and phloem sap, element concentration and species, interactions between elements and cell wall (such as selective binding, cation exchange, adsorption and/or desorption processes on cell wall), synergistic and antagonistic effects among elements are the main mechanisms determining the element concentrations in the different plant parts. These interactions are very complicated and difficult to determine.

Due to ion exchange with the negatively charged cell walls in xylem, most cationic element concentrations tend to decrease in rice plants with increasing distance from the root, except for P, Mo, Ni, and Cu. Most of elements are dominantly concentrated in shoot (they may accumulate 50 ‑ 95 % of the total element mass of the aboveground plant). In contrast, P, Mo, Ni, and Cu are more stored in the grains than in the shoot. Besides, S, Mg, and Zn are also transported quite easily to the grain. This is because Ni, Mg, Zn, and Cu may be transported in xylem sap as soluble organic complexes facilitating their translocation. The elements S, Mo, and P exist as anions sulfate, molybdate, and phosphate respectively, which are repelled at the negatively charged cell, facilitating their transport within the plant.

Most elements have higher concentrations in husk than in grain while Cu, Cd, S, Zn, P, Mg, and Mo accumulate more in grain.

Physiological transfer factors (TF) from soil to the whole aboveground plant cover a very broad range from < 0.00001 to 7.2. Elements like Ti, Zr, Hf, and lanthanides have extremely low TF, whereas P, S, and Mn are taken up by the plant very easily (TF > 1). Harmful elements like Pb, As, Cd, and Mn show a very broad spread of TFs (from average 0.008 to 1.02). Even for one single element, its uptake ability may extremely alter with a spread of transfer factors possibly up to 250-fold (Cs and Na). The great discrepancies may be related to the sensibility of the element phytoavailability under varying soil conditions. Particularly, the transfer factors of As, Pb, and Cd are easily controlled by the soil parameters. This opens up the possibilities to limit their uptake by altering soil factors.

Many soil parameters have inhibitive roles in the element uptake. Sorption, complexing and/or coprecipitation of trace elements on surface of OM, oxides/hydroxides, and clay minerals lead to a decrease in the trace element bioavailability. With regard to the soil factor pH, most cationic elements are solubilized and released in acidic soils, fostering their transferability to plant, whereas in alkaline soils the precipitation of sorbents (oxides/hydroxides) and increased sorption at higher pH are responsible for a decreasing transfer factor. Especially, the uptake of the harmful elements Cd, and Mn in rice grains may be restricted partially by increasing the soil pH.

The dissimilarity of potentially harmful elements in rice grain in three studied regions are summarized as follows:

(1) Mn and As concentrations in Huong River and Mekong River rice grains are similar and higher than in Red River grain, probably relating to differing soil pH-values;

(2) The higher Cd concentrations in rice grains of Red River and Huong River compared to Mekong River's grains is probably due to the amount of used phosphate fertilizer which mostly contains high Cd concentrations;

(3) The average 1.6 times higher content of OM in Mekong River soils is possibly responsible for the visibly higher Pb concentration in Mekong River rice grain.

Health risks of rice consumption

The exposure to different harmful elements by eating rice was evaluated for the three studied areas. The permissible Maximum Concentrations (MC) of iAs, Cd, and Pb in rice grain proposed by the European Union (2006) and FAO/WHO (2014) are used in this study to assess their health risks. Rice grains in Red River and Huong River areas are within the MC of 0.37 mg iAs kg^{-1} (assumption that the portion of iAs is 54 % of the tAs according to Suriyagoda et al. 2008) while 5 % of Mekong River grains exceed this MC. 16 % of the Red River grains surpass the MC for Cd of 0.2 mg kg^{-1} whilst rice grains in Mekong River and Huong River zones are below this limit. 24 % of the Mekong River grains exceed the MC for Pb of 0.2 mg kg^{-1}, whereas all grains Pb in the two other regions contain less than 0.02 mg kg^{-1}.

The tolerable Upper Intake Levels (ULs) for all sources ruled by EFSA are compared with the intake of harmful element by rice consumption. Three of the four rice samples in Huong River, 10 % in Red River, and 12 % in Mekong River exceed the UL of As. Two of four rice grains in Huong River, 40 % in Red River, and 29 % in Mekong River may induce Cd-related health risks. There is no Pb risks for inhabitants in the Red River and Huong River area, but 27 % of the rice grains from the Mekong River area may generate health risks for the people there.

For the cumulative non-cancer risks of the elements As, Cd, Pb, Co, Cu, Mn, Mo, and Ni, all rice grains have a chronic cumulative Hazard Indexes (HI) ≥ 1.4, higher than the safe level of 1 as suggested by USEPA (1989). Red River and Huong River rice grains result in more adverse reactions than Mekong River rice grain. The sum of risk indices of Cd, As, Pb, and Mn contribute 64 – 97 % to the HI-value, in which Cd is generally the highest contributor.

For the cumulative oral cancer risks of As and Pb, all samples overshoot the acceptable cumulative Incremental Lifetime Cancer Risk (∑ILCR) of from 10^{-4} to 10^{-6} according to USEPA (1989). The ∑ILCR values fluctuate from 0.9×10^{-3} to 6.4×10^{-3} (average 2.2×10^{-3}) corresponding to a high level of cancer risk. Of these two elements, As contributes is the vast majority of up to 96 % of ∑ILCR while Pb is a negligible factor with below 4 %. Huong River people are facing the higher cancer risk from rice than the others.

All values calculated in this study are derived from unpolished rice grains, which usually contain the larger amount of beneficial compounds to health (vitamins, protein, fibers, beneficial, nutrient elements) than polished rice grains (Reddy et al. 2017). However, unpolished rice also includes the higher concentration of harmful elements (especially As) than polished rice. Therefore, these health risk assessments may be a little bit different depending on kind of used rice. To restrict the As intake in contaminated area, washing carefully rice with water that is low As concentration is suggested (eliminate partially As-containing bran) (Sun et al. 2012; Halder et al. 2014).

If permissible MCs are recalculated into Tolerable Upper Intake Levels (UL), even the consumption of rice with harmful elements satisfying the MC guideline may also exceed the ULs for Asian population. A simple calculation for a Vietnamese shows this critical dilemma: if a person eats every day 420 g rice containing the maximum permitted concentration of 0.2 mg kg^{-1} for iAs, Cd, and Pb, 0.076 mg of each element would be able to enter the human body. Meanwhile, the ULs calculated for a Vietnamese adult should not surpass 0.110, 0.019, 0.077 mg per day for iAs, Cd, and Pb respectively. Especially for Cd, its allowable concentration value for rice grains should be nearly 4 time lower to fit the upper intake level. A harmonization of regulations between the ULs and MCs is urgent especially for the health situation of large rice-consuming communities. Thus, the regulation for rice's MCs need be related to the local rice consumption. For example, the MCs ruled in China, a country consuming much larger amount of rice (210 g day^{-1} $person^{-1}$) than the European Union (15.6 g day^{-1} $person^{-1}$), are the same as these in Europe (Peoples Republic of China 2018). Instead of 0.2 mg kg^{-1}, the MC of Cd should be below 0.1 mg kg^{-1} for Chinese and 0.5 mg kg^{-1} for Vietnamese.

6.2 An outlook

In view of the importance for paddy soil and rice as the main staple food for billions of people, further research activities should focus on the following issues:

• Improvement in the knowledge base, especially for rice grown in areas with anthropogenic contamination and in regions with high As concentrations in irrigation water and soil.

• Soil concentrations of As, Cd, and Pb do not allow to predict the expected concentration in rice grains, even if soil pH, mineral, and organic phases are taken into consideration. Rice grains from non- or low-polluted soils far below allowed soil limits may surpass critical health levels. Not the soils but the rice grains should be investigated in single areas to get information about health relevance.

• Intensification of research on how to decrease the transfer of harmful elements from contaminated soils into the rice plant. For example, to prevent As transfer from As-rich soils into rice grains, Suriyagoda et al. (2018) proposed the cultivation of rice under aerobic, intermittent flooding or alternate wetting or drying conditions. Under such conditions, Fe-oxides/hydroxides precipitate and bind As. Thus, the availability of As plant is lowered. In addition, the presence of Fe-oxides/hydroxides increases the sorption of other critical elements. To reduce the enrichment of Cd and As in grains that are grown in acidic soils, soil pH should be increased to 6.5 in order to improve sorption and to diminish the uptake of these elements.

• Careful revision and harmonization of the tolerable upper intake level and the maximum concentrations limits for As and Cd in rice to prevent contradictory results (Sauvé 2014). Future studies should focus on As speciation, as well as on As and Cd intake and their health risks.

• Rice cultivars should be systematically tested for the uptake of critical elements (Islam et al. 2016; Xie et al. 2017; Yang et al. 2018).

In future studies, the combination of interacting parameters must be investigated in much more detail to get a better basis for improving practical cultivation and management measures in order to mitigate the accumulation of potentially toxic elements in rice. These parameters are: AWD, role of soil conditioners, redox conditions, pH-value, pore water geochemistry, the concentration of reactive Si and phosphate, influence of cultivars, ROL, formation and composition of plaque, the phases in the rhizosphere soil, the kind and role of iron and organic phases for sorption etc. It should be taken in mind, that a measure minimizing the uptake of one critical element such as As into the rice plant may increase the uptake of another critical element such as Cd, as observed for water management (AWD) practices (Seyfferth et al. 2018).

This kind of research should be complemented by systematic physiological, microbiological, biochemical and species investigations, elucidating the mechanisms behind the transfer of toxic elements from the soil into the rice plant and within the plant - as shown by Kumarathilaka et al. (2018), Wang et al. (2019) and Panthri and Gupta (2019) for As, and by Fahad et al. (2019), Pandey and Dubey (2019), and Roychowdhury et al. (2019) for additional critical elements. Further research is needed to understand the interactions between different elements, the role of pore water chemistry, microbial processes, and speciation of the elements, as well as the plant uptake and accumulation mechanisms especially in rice grains. The resulting new knowledge should help to mitigate the impact of harmful elements on the population but also to understand much better their transfer mechanisms in the soil-water-plant system.

For areas with high concentrations of toxic elements in rice grains, it should be surveyed, if other crops with a lower critical element uptake can be alternatively cultivated.

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Appendix

Appendix A1: Supplementary Material for Chapter 3

Table A1.1 Compilation of wavelengths used by ICP-OES and masses by ICP-MS for the quantification of single elements in soil and plant samples, as well as percentage deviations of measured element concentrations from certified/recommended values of in-house or international reference samples Wissenbach slate TW45, lake sediment GSJ-JLk-1, bush branches and leaves NCS DC 73349, and maize plant WEPAL-IPE-126

Element	For soil				For grain			
	ICP-OES (wavelength: nm)	ICP-MS (mass)	Deviation (%) TW-45 (n=2)	GSJ-JLK-1 (n=2)	ICP-OES (wavelength: nm)	ICP-MS (mass)	Deviation (%) NCS-DC-73349 (n=4)	WEPAL-IPE-126 (n=2)
Al	396.152		0.3	1.5	396.152		-0.4	2.5
As		75	5.7	-6.1		75	-0.3	4.9
Ba	455.403		-3.2	-0.7		135	-1.2	9.5
Bi		209	-4.7	1.6		209	-14.7	-12.6
Ca	422.673.rad		2.2	1.4	317.933.rad		-3.0	-4.5
Cd		111	14.7	-2.0		114	-2.0	-5.7
Ce	413.765		-0.5	-3.2		140	6.2	9.7
Co	230.786		-3.1	1.6	230.786		-5.6	-0.6
Cr	205.560		-12.2	2.0	205.560		10.0	-1.9
Cs		133	-7.0	-7.0		133	-7.5	-0.3
Cu	327.395		1.1	1.8		63	1.4	-0.03
Fe	259.940		-1.8	-2.5	238.204		-15.1	-5.7
Ga	294.363		5	8.4	-	-	-	-
Hf		178	-10	-14		178	8.7	13.6
K	766.491rad		0.5	0.9	766.491.rad		7.4	-0.2
La	408.671		0.7	-4.3		139	-12.8	12.0
Li	670.783		0.9	-1.6		7	14.1	4.9
Mg	279.078rad		-1.3	1.8	279.553.rad		-3.0	-5.8
Mn	257.610		-4.3	-3.1	260.568		3.3	3.0
Mo		98	-2.5	-16	202.032		-1.3	3.3
Na	588.995.rad		0.2	5.3	588.995.rad		-1.3	6.1
Nb	309.417		11	6.7		93	-2.3	9.0
Ni	231.604		-0.9	4.8		62	5.3	-2.3
P	214.914		-2.0	2.1	214.914		-5.7	-0.8
Pb	220.353		-0.7	7.2		208	-9.4	8.9
Rb		85	-6.0	-10.0		85	-8.1	2.2
S	182.562		7.2	4.3	181.972		-2.6	-7.7
Sb		121	-3.0	2.0		121	9.0	10.7
Sc	361.383		0.8	-4.3	361.383		-6.9	-5.9
Sn		120	4.4	-8.5		120	17.4	23.2
Sr	460.733		0.3	-3.9		85	-2.2	12.0
Th		232	0.5	-3.0		232	5.4	3.3
Tl		205	-8.5	-7.0		205	-2.8	-6.2
Ti	368.520		-1.9	-0.1	368.520		8.8	-12.5
V	292.401		1.3	-0.3	-	-	-	-
U		238	4.5	3.0		238	19.3	16.3
Zn	213.857		0.5	-5.4	213.857		-2.1	-5.1
Zr		90	-26.0	-25.0		90	-1.6	22.7

Table A1.2 Concentrations of elements in studied soils along Red River and Huong River in wt. % (n = 30)

Area	Site	pH	LOI	Al	Ca	Fe	K	Mg	Mn	Na	P	S	Ti	Si
Huong River	H1	4.4	8.9	9.1	0.22	3.8	2.22	0.64	0.026	0.26	0.071	0.056	0.51	29
	H5	4.7	6.5	7.9	0.21	4.0	2.08	0.63	0.028	0.32	0.050	0.048	0.50	32
	H6	4.4	4.5	5.9	0.22	2.8	1.70	0.49	0.024	0.30	0.041	0.030	0.46	35
	H7	4.3	5.1	6.4	0.20	3.0	1.80	0.53	0.023	0.30	0.037	0.036	0.46	34
	H8	4.2	7.0	8.0	0.23	3.7	2.10	0.60	0.026	0.32	0.044	0.088	0.50	31
Red River	HN1	7.2	6.6	7.4	0.84	3.9	2.11	0.88	0.060	0.54	0.084	0.062	0.49	31
	HN2	7.1	4.0	6.2	0.70	3.3	1.80	0.75	0.072	0.53	0.077	0.016	0.46	34
	HN3	7.1	5.4	6.2	0.64	3.3	1.83	0.78	0.050	0.54	0.078	0.032	0.44	34
	HN4	4.8	7.0	9.7	0.34	5.0	2.66	1.08	0.051	0.46	0.082	0.055	0.53	28
	HN5	6.7	6.4	7.1	0.51	3.9	1.95	0.85	0.052	0.54	0.085	0.043	0.50	32
	HN6	6.3	5.7	7.7	0.40	4.3	2.16	0.92	0.081	0.52	0.069	0.028	0.54	31
	HN7	5.6	6.8	8.6	0.32	4.4	2.38	0.97	0.034	0.48	0.059	0.033	0.54	30
	HN8	5.2	6.3	8.6	0.30	4.4	2.32	0.97	0.034	0.50	0.060	0.036	0.55	30
	HN9	5.5	6.5	8.6	0.35	4.3	2.32	0.99	0.033	0.50	0.097	0.040	0.55	30
	HN10	4.8	10.0	8.8	0.25	5.5	2.05	0.47	0.021	0.31	0.073	0.100	0.48	28
	HN11	6.0	5.0	8.1	0.45	4.3	2.35	0.97	0.064	0.54	0.126	0.025	0.51	31
	PT1	5.9	3.5	3.9	0.46	2.3	1.16	0.43	0.033	0.58	0.094	0.018	0.43	38
	PT2	7.0	4.8	8.0	1.16	4.6	2.54	1.16	0.090	1.12	0.081	0.016	0.55	30
	PT3	6.9	6.4	6.6	0.80	3.7	1.92	0.90	0.056	0.76	0.106	0.046	0.48	32
	PT4	7.3	4.9	7.2	1.07	4.1	2.07	1.01	0.077	0.75	0.089	0.018	0.49	32
	PT5	5.1	11.1	8.9	0.61	6.4	1.81	0.71	0.072	0.35	0.205	0.869	0.45	26
	PT6	6.2	7.1	8.0	0.30	9.2	1.11	0.44	0.043	0.23	0.059	0.066	0.41	29
	PT7	6.6	7.9	8.5	0.33	8.0	0.83	0.34	0.029	0.20	0.061	0.066	0.41	29
	PT8	6.4	6.5	6.6	0.71	3.6	1.86	0.77	0.052	0.68	0.106	0.054	0.45	32
	PT9	7.1	6.3	6.2	1.48	3.6	1.84	0.92	0.072	0.64	0.134	0.046	0.43	32
	PT10	5.4	10.1	9.4	0.52	5.0	2.49	1.01	0.066	0.44	0.083	0.558	0.51	27
	PT11	6.7	8.1	8.5	0.55	4.3	2.11	0.64	0.058	0.32	0.085	0.058	0.53	30
	ND1	6.2	3.7	4.3	0.38	2.0	1.51	0.33	0.045	0.59	0.088	0.024	0.33	38
	ND2	5.6	9.2	8.7	0.39	4.5	2.35	0.92	0.042	0.46	0.105	0.082	0.52	29
	ND3	5.7	7.2	9.1	0.41	4.7	2.46	1.03	0.046	0.48	0.096	0.040	0.54	29

Table A1.2 *(cont.)* Concentrations of elements in studied soils along Red River and Huong River in mg kg^{-1} (n = 30)

Area	Site	As	Ba	Bi	Cd	Ce	Co	Cr	Cs	Cu	Ga	Hf	La	Li	Mo
Huong River	H1	12.5	493	0.79	0.34	103	17	47	7.8	35	22	3.4	47	30	1.11
	H5	16.8	496	0.60	0.22	89	14	42	6.6	29	19	3.7	45	29	1.21
	H6	11.2	404	0.40	0.19	63	10	30	4.9	20	14	4.1	34	21	0.82
	H7	12.3	428	0.45	0.20	68	11	33	5.4	23	16	3.7	36	23	0.92
	H8	15.0	481	0.57	0.27	90	14	43	6.8	28	19	4.0	45	29	1.28
Red River	HN1	17.8	399	0.51	0.34	81	17	58	8.8	38	19	4.8	42	44	0.70
	HN2	15.6	381	0.43	0.30	79	14	48	6.8	33	16	5.0	39	36	0.41
	HN3	15.1	374	0.46	0.34	70	14	51	7.0	39	15	4.3	36	36	0.42
	HN4	24.3	496	0.79	0.43	99	21	71	12.0	51	24	4.9	48	56	1.04
	HN5	17.9	395	0.40	0.37	79	17	63	8.0	39	18	4.5	39	43	0.53
	HN6	23.7	427	0.40	0.37	88	19	66	9.1	38	19	4.8	43	46	0.67
	HN7	19.7	442	0.48	0.32	93	19	77	10.7	41	22	4.5	45	52	0.63
	HN8	19.8	439	0.49	0.31	95	19	80	10.6	43	22	4.8	46	52	0.61
	HN9	16.7	449	0.56	0.37	95	20	93	10.5	45	22	4.8	47	52	0.53
	HN10	30.9	354	0.53	0.32	93	13	78	10.7	38	23	4.5	45	43	1.35
	HN11	22.0	453	0.64	0.32	87	18	67	10.2	43	20	4.3	43	47	0.69
	PT1	9.5	315	0.43	0.24	71	7	32	3.2	28	11	4.5	34	18	0.46
	PT2	45.1	815	3.66	0.53	184	18	49	5.6	86	24	2.8	90	32	1.93
	PT3	21.9	439	0.86	0.47	97	15	50	6.0	52	17	4.9	45	34	0.78
	PT4	46.8	523	3.45	0.56	110	16	55	6.5	84	20	4.0	51	32	1.35
	PT5	49.7	376	1.06	6.46	157	50	72	8.6	885	23	3.5	56	41	2.50
	PT6	26.3	209	0.62	0.38	61	11	128	4.7	59	27	1.9	33	23	2.21
	PT7	18.1	159	0.60	0.20	77	8	125	3.7	41	26	1.6	37	19	2.41
	PT8	24.6	439	1.25	0.46	79	15	58	6.2	56	17	3.5	38	32	0.87
	PT9	28.5	423	1.43	0.49	80	14	59	6.5	61	16	3.4	39	34	0.78
	PT10	21.9	455	0.72	0.46	98	21	90	11.3	52	24	4.5	47	55	1.27
	PT11	18.5	376	0.65	0.49	104	16	61	10.2	37	22	3.7	45	35	1.02
	ND1	10.7	342	0.22	0.17	55	8	40	4.5	41	10	2.8	27	28	0.85
	ND2	20.2	428	0.63	0.34	92	19	85	10.9	46	22	4.5	45	56	1.18
	ND3	23.9	467	1.02	0.40	100	20	83	11.1	55	23	4.7	47	54	0.77

Table A1.2 *(cont.)* Concentrations of elements in studied soils along Red River and Huong River in mg kg^{-1} (n = 30)

Area	Site	Nb	Ni	Pb	Rb	Sb	Sc	Sn	Sr	Th	Tl	U	V	Zn	Zr
Huong	H1	19	36	38	133	1.77	16	5.7	39	23	0.70	5.2	115	114	96
River	H5	17	31	32	122	1.72	14	4.6	41	20	0.63	4.7	103	85	108
	H6	14	22	23	98	1.32	11	3.6	40	16	0.49	3.9	78	64	119
	H7	15	24	24	105	1.46	12	4.1	39	17	0.53	4.0	86	70	106
	H8	18	30	31	126	1.63	15	4.8	45	20	0.62	4.9	104	84	120
Red River	HN1	20	43	35	128	1.88	13	4.0	81	17	0.62	3.8	105	96	147
	HN2	17	35	31	108	1.60	10	3.5	76	16	0.53	3.4	88	85	154
	HN3	17	35	33	112	1.62	10	3.4	80	14	0.54	3.1	87	100	132
	HN4	25	58	59	164	2.54	17	5.5	79	20	0.81	4.3	137	131	151
	HN5	19	42	34	114	1.85	13	3.7	73	15	0.58	3.5	104	98	143
	HN6	21	45	38	128	2.03	14	3.9	75	17	0.62	3.7	113	98	152
	HN7	22	49	41	143	1.91	15	4.8	78	18	0.71	3.8	123	107	144
	HN8	22	48	44	141	1.96	15	4.4	78	18	0.71	3.9	122	107	152
	HN9	23	50	45	140	2.08	15	4.5	82	18	0.71	4.0	122	111	149
	HN10	23	35	39	134	3.48	14	4.8	81	19	0.71	4.2	128	89	149
	HN11	21	46	42	143	1.89	14	5.2	79	17	0.70	3.7	116	132	142
	PT1	21	19	40	64	1.04	6	3.8	78	13	0.32	2.9	57	70	143
	PT2	38	39	69	133	2.85	12	8.0	170	20	0.59	4.3	108	139	79
	PT3	24	36	69	106	1.77	11	5.1	94	17	0.53	3.4	94	103	154
	PT4	29	38	83	117	2.75	12	7.1	110	16	0.56	3.7	100	132	127
	PT5	20	51	79	109	2.78	16	5.8	69	20	0.77	6.7	117	1725	112
	PT6	21	27	55	65	1.35	19	3.3	35	24	0.38	3.8	165	139	61
	PT7	20	23	52	49	1.16	17	3.7	30	30	0.31	4.2	152	83	47
	PT8	18	34	75	104	2.22	11	4.8	100	15	0.54	3.3	92	113	113
	PT9	17	35	86	108	2.09	10	5.2	102	15	0.53	3.1	89	127	108
	PT10	23	54	49	151	1.72	17	5.3	79	18	0.78	4.2	139	152	142
	PT11	22	38	50	133	2.85	15	6.7	43	18	0.71	4.2	119	124	118
	ND1	13	19	27	86	1.13	7	3.9	87	9	0.41	2.8	55	65	93
	ND2	23	54	51	143	2.01	15	4.9	81	17	0.71	4.2	129	119	140
	ND3	24	53	66	146	2.54	16	5.8	84	19	0.76	4.2	129	130	153

Table A1.3 Concentrations of elements in unpolished rice in mg kg^{-1} dry matter (n = 24)

Area	Site	Al	Ca	Fe	K	Mg	Mn	Na	P	S	Ti
Huong	H1	15	161	19.3	3348	1262	21	6.4	3680	1205	0.86
River	H5	<4	132	14.1	2983	1347	24	8.4	3407	927	0.27
	H6	<4	118	9.1	2453	1104	26	3.3	2656	1004	0.09
	H7	<4	143	9.1	2995	1247	23	3.9	3198	1069	0.09
Red	HN1	<4	145	11.7	3103	1511	18	6.0	3820	1262	0.13
River	HN2	<4	146	13.2	2988	1468	23	5.2	3833	1069	0.09
	HN3	<4	134	12.5	2942	1441	20	5.3	3738	1127	0.11
	HN5	<4	139	11.5	2689	1386	23	3.2	3515	1122	<0.05
	HN6	<4	125	9.9	2720	1241	29	3.9	3145	934	<0.05
	HN7	<4	128	10.0	2826	1236	23	4.1	3216	986	<0.05
	HN8	<4	114	8.3	2356	1205	20	3.5	2859	884	<0.05
	HN9	<4	150	12.2	2761	1376	29	2.8	3527	969	0.08
	HN10	<4	139	9.1	2978	1352	45	3.6	3590	1066	0.06
	HN11	<4	137	12.5	3168	1447	26	4.3	3800	1119	0.06
	PT1	<4	122	10.1	2870	1369	24	3.3	3462	1054	<0.05
	PT3	13	106	9.0	3021	1502	17	2.8	3637	890	0.06
	PT4	<4	139	13.5	2512	1126	12	2.7	2815	1148	0.09
	PT5	<4	145	13.3	3157	1591	20	4.7	4167	1256	0.10
	PT6	<4	145	11.2	2866	1468	17	6.7	3794	1067	<0.05
	PT7	<4	163	10.8	2955	1422	18	6.3	3709	1330	<0.05
	PT8	<4	133	11.2	3099	1584	24	3.9	4024	1149	<0.05
	PT9	<4	122	10.4	3215	1432	18	3.6	3682	1104	<0.05
	PT10	<4	124	9.8	3352	1475	16	5.6	3912	1226	0.06
	PT11	<4	131	9.0	2620	1248	21	3.2	3273	1191	<0.05

Table A1.3 *(cont.)* Concentrations of elements in unpolished rice in mg kg^{-1} dry matter (n = 24)

Area	Site	As	Ba	Bi	Cd	Ce	Co	Cr	Cs	Cu	Hf	La	Li	Mo	Nb
Huong	H1	0.34	1.69	0.0045	0.100	0.0144	0.069	<0.1	0.111	3.06	0.0011	0.0079	0.031	0.59	<0.034
River	H5	0.34	2.07	0.0003	0.073	0.0048	0.066	<0.1	0.214	3.80	0.0005	0.0027	0.009	0.48	<0.034
	H6	0.13	0.92	0.0003	0.125	0.0020	0.133	<0.1	0.989	4.69	<0.0002	0.0011	0.011	0.77	<0.034
	H7	0.28	1.36	0.0015	0.043	0.0020	0.062	<0.1	0.389	2.76	0.0002	0.0011	<0.006	0.92	<0.034
Red	HN1	0.34	1.25	<0.0002	0.005	0.0025	0.010	<0.1	0.005	1.69	<0.0002	0.0014	<0.006	0.44	<0.034
River	HN2	0.16	0.75	0.0002	0.012	0.0012	0.028	<0.1	0.020	4.51	<0.0002	0.0007	<0.006	0.53	<0.034
	HN3	0.27	0.66	<0.0002	0.009	0.0016	0.019	<0.1	0.016	3.19	<0.0002	0.0009	<0.006	1.29	<0.034
	HN5	0.13	3.64	<0.0002	0.034	<0.0006	0.020	<0.1	0.025	4.15	<0.0002	0.0003	<0.006	0.47	<0.034
	HN6	0.23	1.48	0.0002	0.129	<0.0006	0.020	<0.1	0.023	2.12	0.0015	0.0004	<0.006	0.73	<0.034
	HN7	0.16	0.99	0.0003	0.127	0.0007	0.016	<0.1	0.020	3.43	0.0014	0.0004	<0.006	0.70	<0.034
	HN8	0.11	0.96	<0.0002	0.264	<0.0006	0.009	<0.1	0.049	3.73	<0.0002	<0.0003	<0.006	0.44	<0.034
	HN9	0.27	1.75	0.0003	0.322	0.0011	0.020	<0.1	0.006	3.92	<0.0002	0.0006	<0.006	0.54	<0.034
	HN10	0.19	0.83	<0.0002	0.964	0.0008	0.031	<0.1	0.046	4.38	<0.0002	0.0004	<0.006	0.22	<0.034
	HN11	0.20	1.04	0.0004	0.050	<0.0006	0.021	<0.1	0.011	4.15	<0.0002	0.0003	<0.006	0.89	<0.034
	PT1	0.13	1.52	<0.0002	0.148	0.0007	0.008	<0.1	0.035	4.32	<0.0002	0.0004	0.009	0.94	<0.034
	PT3	0.26	1.63	0.0004	0.030	0.0010	0.013	<0.1	0.064	4.26	<0.0002	0.0006	<0.006	0.85	<0.034
	PT4	0.13	0.44	<0.0002	0.029	0.0008	0.016	<0.1	0.010	8.52	<0.0002	0.0004	<0.006	0.71	<0.034
	PT5	0.12	1.62	<0.0002	0.039	0.0016	0.036	<0.1	0.049	2.90	0.0006	0.0008	0.007	0.22	<0.034
	PT6	0.26	0.92	<0.0002	0.003	0.0007	0.006	<0.1	0.149	0.85	<0.0002	0.0004	<0.006	0.19	<0.034
	PT7	0.34	0.53	<0.0002	0.004	<0.0006	0.005	<0.1	0.168	0.72	<0.0002	<0.0003	<0.006	0.25	<0.034
	PT8	0.27	1.49	0.0007	0.040	<0.0006	0.024	<0.1	0.046	2.77	<0.0002	<0.0003	<0.006	1.19	<0.034
	PT9	0.23	1.11	0.0006	0.026	<0.0006	0.014	<0.1	0.012	2.91	<0.0002	<0.0003	0.009	1.18	<0.034
	PT10	0.16	1.51	<0.0002	0.002	<0.0006	0.004	<0.1	0.006	0.86	<0.0002	<0.0003	<0.006	0.18	<0.034
	PT11	0.14	1.16	0.0002	0.078	<0.0006	0.013	<0.1	0.018	3.10	<0.0002	<0.0003	<0.006	0.47	<0.034

Table A1.3 *(cont.)* Concentrations of elements in unpolished rice in mg kg^{-1} dry matter (n = 24)

Area	Site	Ni	Pb	Rb	Sb	Sc	Sn	Sr	Th	Tl	U	Zn	Zr
Huong	H1	0.67	0.02	19.3	0.0011	0.005	<0.06	0.44	0.0025	<0.0002	0.0017	32	0.040
River	H5	0.38	<0.02	44.5	<0.0006	<0.003	<0.06	0.53	0.0007	<0.0002	0.0005	27	0.020
	H6	2.24	<0.02	60.2	<0.0006	<0.003	<0.06	0.44	0.0002	0.0004	0.0002	24	<0.007
	H7	0.53	<0.02	53.5	<0.0006	<0.003	<0.06	0.46	0.0002	<0.0002	0.0001	25	0.007
Red	HN1	0.06	<0.02	2.6	0.0006	<0.003	<0.06	0.37	0.0004	<0.0002	0.0002	17	<0.007
River	HN2	0.36	<0.02	11.8	<0.0006	<0.003	<0.06	0.39	0.0002	<0.0002	0.0001	28	<0.007
	HN3	0.11	<0.02	9.1	<0.0006	<0.003	<0.06	0.41	0.0003	0.0003	0.0001	21	<0.007
	HN5	0.34	<0.02	8.6	<0.0006	<0.003	<0.06	0.37	<0.0002	0.0002	<0.0001	25	0.066
	HN6	0.44	<0.02	11.3	<0.0006	<0.003	<0.06	0.30	<0.0002	0.0002	<0.0001	21	0.060
	HN7	0.43	<0.02	10.2	<0.0006	<0.003	<0.06	0.25	<0.0002	0.0002	<0.0001	24	<0.007
	HN8	0.89	<0.02	13.1	<0.0006	<0.003	<0.06	0.25	<0.0002	<0.0002	<0.0001	26	<0.007
	HN9	0.62	<0.02	4.0	<0.0006	<0.003	<0.06	0.43	0.0002	0.0003	<0.0001	26	<0.007
	HN10	1.02	<0.02	11.5	<0.0006	<0.003	<0.06	0.29	<0.0002	<0.0002	<0.0001	28	<0.007
	HN11	0.31	<0.02	7.3	<0.0006	<0.003	<0.06	0.28	<0.0002	0.0002	<0.0001	25	<0.007
	PT1	0.84	<0.02	27.3	<0.0006	<0.003	<0.06	0.42	<0.0002	<0.0002	<0.0001	25	<0.007
	PT3	0.14	<0.02	35.6	0.0009	<0.003	<0.06	0.37	<0.0002	0.0003	<0.0001	19	<0.007
	PT4	0.84	<0.02	6.5	<0.0006	<0.003	<0.06	0.18	<0.0002	0.0003	<0.0001	25	<0.007
	PT5	0.08	<0.02	11.0	<0.0006	<0.003	<0.06	0.49	0.0003	0.0002	0.0001	28	0.021
	PT6	0.03	<0.02	26.8	<0.0006	<0.003	<0.06	0.45	<0.0002	0.0002	<0.0001	20	<0.007
	PT7	0.05	<0.02	20.6	<0.0006	<0.003	<0.06	0.44	<0.0002	0.0002	<0.0001	19	<0.007
	PT8	0.08	<0.02	22.3	<0.0006	<0.003	<0.06	0.37	<0.0002	0.0002	<0.0001	28	<0.007
	PT9	0.07	<0.02	11.4	<0.0006	<0.003	<0.06	0.34	<0.0002	0.0002	<0.0001	24	<0.007
	PT10	0.08	<0.02	4.1	<0.0006	<0.003	<0.06	0.45	<0.0002	<0.0002	<0.0001	14	<0.007
	PT11	0.20	<0.02	9.2	<0.0006	<0.003	<0.06	0.28	<0.0002	0.0002	<0.0001	24	<0.007

Table A1.4 Transfer factors of selected elements from soil to unpolished rice (n = 24)

Area	Site	Al	Ca	Fe	K	Mg	Mn	Na	P	S	Ti
Huong	H1	0.00017	0.073	0.00050	0.15	0.20	0.081	0.0024	5.2	2.2	0.00017
River	H5	<0.00005	0.062	0.00036	0.14	0.21	0.085	0.0026	6.8	1.9	0.00005
	H6	<0.00005	0.052	0.00033	0.14	0.22	0.111	0.0011	6.4	3.4	0.00002
	H7	<0.00005	0.070	0.00030	0.17	0.23	0.100	0.0013	8.5	3.0	0.00002
Red	HN1	<0.00005	0.017	0.00030	0.15	0.17	0.030	0.0011	4.5	2.0	0.00003
River	HN2	<0.00005	0.021	0.00040	0.17	0.20	0.031	0.0010	5.0	6.5	0.00002
	HN3	<0.00005	0.021	0.00038	0.16	0.19	0.039	0.0010	4.8	3.5	0.00002
	HN5	<0.00005	0.027	0.00029	0.14	0.16	0.044	0.0006	4.1	2.6	<0.00001
	HN6	<0.00005	0.031	0.00023	0.13	0.14	0.036	0.0007	4.6	3.3	<0.00001
	HN7	<0.00005	0.040	0.00023	0.12	0.13	0.067	0.0009	5.4	3.0	<0.00001
	HN8	<0.00005	0.039	0.00019	0.10	0.12	0.058	0.0007	4.8	2.5	<0.00001
	HN9	<0.00005	0.043	0.00028	0.12	0.14	0.089	0.0006	3.7	2.4	0.00001
	HN10	<0.00005	0.056	0.00017	0.15	0.28	0.219	0.0011	4.9	1.1	0.00001
	HN11	<0.00005	0.030	0.00029	0.13	0.15	0.041	0.0008	3.0	4.5	0.00001
	PT1	<0.00005	0.026	0.00043	0.25	0.32	0.074	0.0006	3.7	5.8	<0.00001
	PT3	0.00020	0.013	0.00024	0.16	0.17	0.031	0.0004	3.4	1.9	0.00001
	PT4	<0.00005	0.013	0.00033	0.12	0.11	0.015	0.0004	3.2	6.4	0.00002
	PT5	<0.00005	0.024	0.00025	0.17	0.22	0.028	0.0013	2.0	0.1	0.00002
	PT6	<0.00005	0.048	0.00012	0.26	0.34	0.039	0.0029	6.4	1.6	<0.00001
	PT7	<0.00005	0.049	0.00014	0.36	0.42	0.062	0.0032	6.1	2.0	<0.00001
	PT8	<0.00005	0.019	0.00031	0.17	0.21	0.046	0.0006	3.8	2.1	<0.00001
	PT9	<0.00005	0.008	0.00029	0.17	0.15	0.025	0.0006	2.7	2.4	<0.00001
	PT10	<0.00005	0.024	0.00019	0.13	0.15	0.024	0.0013	4.7	0.2	0.00001
	PT11	<0.00005	0.024	0.00021	0.12	0.19	0.036	0.0010	3.8	2.1	<0.00001

Table A1.4 *(cont.)* Transfer factors of elements from soil to unpolished rice (n = 24)

Area	Site	As	Ba	Bi	Cd	Ce	Co	Cr	Cs	Cu	Hf	La	Li	Mo	Nb
Huong River	H1	0.027	0.003	0.0057	0.291	0.00014	0.0040	<0.001	0.0143	0.088	0.00032	0.00017	0.0010	0.54	<0.002
	H5	0.020	0.004	0.0005	0.333	0.00005	0.0045	<0.001	0.0324	0.130	0.00013	0.00006	0.0003	0.40	<0.002
	H6	0.012	0.002	0.0008	0.658	0.00003	0.0134	<0.001	0.2021	0.232	<0.00005	0.00003	0.0005	0.94	<0.002
	H7	0.023	0.003	0.0034	0.209	0.00003	0.0057	<0.001	0.0717	0.120	0.00005	0.00003	<0.0001	1.00	<0.002
Red River	HN1	0.019	0.003	<0.0003	0.014	0.00003	0.0006	<0.001	0.0006	0.044	<0.00005	0.00003	<0.0001	0.62	<0.002
	HN2	0.010	0.002	0.0006	0.038	0.00002	0.0020	<0.001	0.0029	0.135	<0.00005	0.00002	<0.0001	1.30	<0.002
	HN3	0.018	0.002	<0.0003	0.028	0.00002	0.0014	<0.001	0.0023	0.083	<0.00005	0.00002	<0.0001	3.06	<0.002
	HN5	0.008	0.009	<0.0003	0.091	<0.00001	0.0012	<0.001	0.0031	0.106	<0.00005	0.00001	<0.0001	0.89	<0.002
	HN6	0.010	0.003	0.0006	0.347	<0.00001	0.0010	<0.001	0.0026	0.056	0.00034	0.00001	<0.0001	1.08	<0.002
	HN7	0.008	0.002	0.0006	0.392	0.00001	0.0009	<0.001	0.0019	0.085	0.00030	0.00001	<0.0001	1.11	<0.002
	HN8	0.005	0.002	<0.0003	0.857	<0.00001	0.0005	<0.001	0.0046	0.087	<0.00005	<0.00001	<0.0001	0.73	<0.002
	HN9	0.016	0.004	0.0005	0.873	0.00001	0.0010	<0.001	0.0005	0.088	<0.00005	0.00001	<0.0001	1.03	<0.002
	HN10	0.006	0.002	<0.0003	2.992	0.00001	0.0024	<0.001	0.0042	0.116	<0.00005	0.00001	<0.0001	0.16	<0.002
	HN11	0.009	0.002	0.0007	0.158	<0.00001	0.0012	<0.001	0.0011	0.096	<0.00005	0.00001	<0.0001	1.28	<0.002
	PT1	0.013	0.005	<0.0003	0.621	0.00001	0.0011	<0.001	0.0110	0.155	<0.00005	0.00001	0.0005	2.02	<0.002
	PT3	0.012	0.004	0.0005	0.064	0.00001	0.0009	0.003	0.0108	0.082	<0.00005	0.00001	<0.0001	1.09	<0.002
	PT4	0.003	0.001	<0.0003	0.051	0.00001	0.0010	<0.001	0.0015	0.101	<0.00005	0.00001	<0.0001	0.53	<0.002
	PT5	0.002	0.004	<0.0003	0.006	0.00001	0.0007	<0.001	0.0057	0.003	0.000158	0.00001	0.0002	0.09	<0.002
	PT6	0.010	0.004	<0.0003	0.007	0.00001	0.0005	<0.001	0.0315	0.014	<0.00005	0.00001	<0.0001	0.09	<0.002
	PT7	0.019	0.003	<0.0003	0.019	<0.00001	0.0007	<0.001	0.0455	0.018	<0.00005	<0.00001	<0.0001	0.11	<0.002
	PT8	0.011	0.003	0.0005	0.088	<0.00001	0.0017	<0.001	0.0073	0.050	<0.00005	<0.00001	<0.0001	1.36	<0.002
	PT9	0.008	0.003	0.0004	0.053	<0.00001	0.0010	<0.001	0.0019	0.048	<0.00005	<0.00001	0.0005	1.51	<0.002
	PT10	0.007	0.003	<0.0003	0.005	<0.00001	0.0002	0.001	0.0005	0.017	<0.00005	<0.00001	<0.0001	0.14	<0.002
	PT11	0.007	0.003	0.0004	0.160	<0.00001	0.0008	<0.001	0.0018	0.083	<0.00005	<0.00001	<0.0001	0.46	<0.002

Table A1.4 *(cont.)* Transfer factors of elements from soil to unpolished rice (n = 24)

Area	Site	Ni	Pb	Rb	Sb	Sc	Sn	Sr	Th	Tl	U	Zn	Zr
Huong	H1	0.019	0.0005	0.14	0.0006	0.0003	<0.02	0.011	0.00011	<0.0003	0.00032	0.28	0.00042
River	H5	0.012	<0.0005	0.36	<0.0003	<0.0003	<0.02	0.013	0.00004	<0.0003	0.00011	0.32	0.00018
	H6	0.104	<0.0005	0.62	<0.0003	<0.0003	<0.02	0.011	0.00002	0.0009	0.00004	0.37	<0.00006
	H7	0.022	<0.0005	0.51	<0.0003	<0.0003	<0.02	0.012	0.00001	<0.0003	0.00004	0.36	0.00006
Red	HN1	0.001	<0.0005	0.02	0.0003	<0.0003	<0.02	0.005	0.00002	<0.0003	0.00006	0.18	<0.00006
River	HN2	0.010	<0.0005	0.11	<0.0003	<0.0003	<0.02	0.005	0.00001	<0.0003	0.00003	0.34	<0.00006
	HN3	0.003	<0.0005	0.08	<0.0003	<0.0003	<0.02	0.005	0.00002	0.0005	0.00004	0.21	<0.00006
	HN5	0.008	<0.0005	0.08	<0.0003	<0.0003	<0.02	0.005	<0.00001	0.0003	<0.00002	0.25	0.00046
	HN6	0.010	<0.0005	0.09	<0.0003	<0.0003	<0.02	0.004	<0.00001	0.0004	<0.00002	0.21	0.00039
	HN7	0.009	<0.0005	0.07	<0.0003	<0.0003	<0.02	0.003	<0.00001	0.0003	<0.00002	0.22	<0.00006
	HN8	0.018	<0.0005	0.09	<0.0003	<0.0003	<0.02	0.003	<0.00001	<0.0003	<0.00002	0.24	<0.00006
	HN9	0.013	<0.0005	0.03	<0.0003	<0.0003	<0.02	0.005	0.00001	0.0004	<0.00002	0.24	<0.00006
	HN10	0.029	<0.0005	0.09	<0.0003	<0.0003	<0.02	0.004	<0.00001	<0.0003	<0.00002	0.32	<0.00006
	HN11	0.007	<0.0005	0.05	<0.0003	<0.0003	<0.02	0.004	<0.00001	0.0003	<0.00002	0.19	<0.00006
	PT1	0.045	<0.0005	0.42	<0.0003	<0.0003	<0.02	0.005	<0.00001	<0.0003	<0.00002	0.35	<0.00006
	PT3	0.004	<0.0005	0.34	0.0005	<0.0003	<0.02	0.004	<0.00001	0.0006	<0.00002	0.18	<0.00006
	PT4	0.022	<0.0005	0.06	<0.0003	<0.0003	<0.02	0.002	<0.00001	0.0005	<0.00002	0.19	<0.00006
	PT5	0.002	<0.0005	0.10	<0.0003	<0.0003	<0.02	0.007	0.00001	0.0003	0.00002	0.02	0.00019
	PT6	0.001	<0.0005	0.41	<0.0003	<0.0003	<0.02	0.013	<0.00001	0.0006	<0.00002	0.14	<0.00006
	PT7	0.002	<0.0005	0.42	<0.0003	<0.0003	<0.02	0.015	<0.00001	0.0006	<0.00002	0.23	<0.00006
	PT8	0.002	<0.0005	0.22	<0.0003	<0.0003	<0.02	0.004	<0.00001	0.0003	<0.00002	0.25	<0.00006
	PT9	0.002	<0.0005	0.11	<0.0003	<0.0003	<0.02	0.003	<0.00001	0.0004	<0.00002	0.19	<0.00006
	PT10	0.001	<0.0005	0.03	<0.0003	<0.0003	<0.02	0.006	<0.00001	<0.0003	<0.00002	0.09	<0.00006
	PT11	0.005	<0.0005	0.07	<0.0003	<0.0003	<0.02	0.007	<0.00001	0.0003	<0.00002	0.19	<0.00006

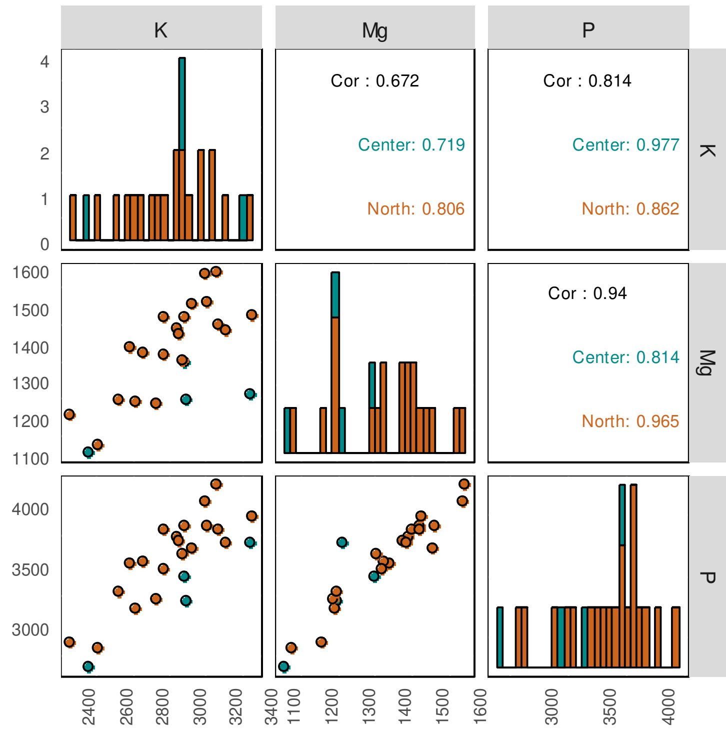


Fig. A1.1 Correlation matrix of K, Mg, and P concentrations in unpolished rice grains (mg kg^{-1})

Appendix A2: Supplementary Material for Chapter 4

Table A2.1 Coordinates of sampling locations in the Mekong River Delta area, pH-values and concentrations of main elements and LOI in paddy soils in wt. % (n = 78)

Sites	Coordinate		pH	LOI	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO	Na_2O	P_2O_5	S	TiO_2	SiO_2
	E	N													
MK-1	105.1789	10.84005	6.4	16.2	15.6	1.07	5.11	2.28	1.19	0.079	0.56	0.15	0.07	0.72	57.0
MK-2	105.1726	10.83846	4.7	11.8	20.3	0.55	5.32	2.70	1.26	0.033	0.52	0.11	0.05	0.79	56.6
MK-3	105.2876	10.82348	5.1	8.6	16.2	0.55	5.83	2.51	1.30	0.040	0.72	0.16	0.04	0.87	63.1
MK-4	105.3117	10.83041	6.0	5.5	13.1	0.63	5.21	2.25	1.17	0.081	0.83	0.12	0.03	0.79	70.3
MK-5	105.3077	10.82734	5.6	6.8	16.1	0.52	6.39	2.59	1.33	0.077	0.75	0.15	0.03	0.88	64.4
MK-6	105.2991	10.82513	6.4	4.7	13.0	0.59	5.27	2.18	1.16	0.086	0.86	0.13	0.02	0.79	71.2
MK-7	105.3071	10.79540	5.1	8.6	15.0	0.56	5.32	2.26	1.09	0.041	0.71	0.13	0.04	0.82	65.4
MK-8	105.3047	10.79752	5.7	7.4	14.6	0.49	6.26	2.25	1.14	0.161	0.72	0.19	0.02	0.82	66.0
MK-9	105.3082	10.78972	5.0	8.9	18.5	0.50	6.30	2.65	1.32	0.052	0.67	0.19	0.05	0.81	60.1
MK-10	105.1407	10.72770	4.8	11.7	19.8	0.54	5.77	2.78	1.33	0.028	0.53	0.20	0.09	0.80	56.5
MK-11	105.2111	10.80318	5.3	6.3	11.9	0.49	4.69	1.98	0.99	0.043	0.83	0.28	0.05	0.74	71.7
MK-12	105.1952	10.79276	5.5	5.8	14.5	0.54	5.93	2.38	1.28	0.098	0.80	0.13	0.03	0.82	67.7
MK-13	105.1966	10.80347	4.7	9.5	16.6	0.43	6.32	2.51	1.26	0.044	0.64	0.20	0.04	0.86	61.7
MK-14	105.2539	10.16000	4.9	7.8	13.3	0.45	4.49	2.17	1.02	0.029	0.69	0.13	0.06	0.72	69.1
MK-15	105.2278	10.79780	4.9	7.9	13.2	0.51	5.37	2.17	1.17	0.058	0.84	0.17	0.05	0.79	67.7
MK-16	105.2187	10.80072	5.7	7.1	13.3	0.60	5.42	2.17	1.16	0.067	0.83	0.18	0.03	0.83	68.3
MK-17	105.2050	10.77340	5.1	7.9	13.7	0.54	5.51	2.18	1.08	0.066	0.72	0.28	0.04	0.76	67.2
MK-18	105.1952	10.77515	4.6	10.7	17.6	0.46	5.96	2.64	1.28	0.036	0.63	0.24	0.08	0.83	59.6
MK-19	105.2079	10.79831	5.1	6.6	13.5	0.55	5.46	2.20	1.16	0.094	0.77	0.32	0.03	0.79	68.5
MK-20	105.2653	10.76141	4.7	8.2	15.1	0.46	5.92	2.39	1.22	0.053	0.69	0.23	0.05	0.84	64.8
MK-21	105.2436	10.74276	4.8	9.5	14.8	0.50	4.70	2.21	1.01	0.026	0.68	0.21	0.07	0.78	65.6
MK-22	105.2535	10.68282	5.1	13.1	17.3	0.55	4.43	2.15	0.93	0.024	0.50	0.20	0.07	0.79	59.9
MK-23	105.2726	10.65025	5.4	18.8	17.4	0.81	3.81	2.05	0.93	0.022	0.45	0.15	0.15	0.74	54.7
MK-24	105.2934	10.62049	5.0	12.1	17.8	0.60	4.58	2.19	0.91	0.025	0.52	0.17	0.07	0.82	60.2
MK-25	105.3058	10.59924	4.9	10.3	15.4	0.52	4.17	2.22	1.01	0.019	0.64	0.15	0.07	0.77	64.8
MK-26	106.4413	10.35912	4.9	12.0	19.2	0.43	6.78	2.53	1.08	0.042	0.49	0.18	0.06	0.88	56.3
MK-27	106.4850	10.34935	5.7	9.7	15.6	0.44	5.72	2.32	1.10	0.055	0.61	0.09	0.06	1.01	63.3
MK-30	105.4629	10.43315	4.5	9.0	18.7	0.38	5.84	2.69	1.22	0.023	0.58	0.13	0.06	0.84	60.5
MK-31	105.4434	10.55026	5.0	9.2	16.7	0.49	6.24	2.56	1.27	0.045	0.66	0.26	0.05	0.81	61.8
MK-32	105.4503	10.54120	4.5	10.3	17.1	0.42	5.37	2.54	1.24	0.030	0.63	0.17	0.06	0.85	61.3
MK-33	105.4884	10.49884	4.5	10.2	17.9	0.42	5.27	2.59	1.23	0.027	0.62	0.21	0.07	0.84	60.6
MK-34	105.4842	10.49025	4.9	9.5	16.4	0.48	5.33	2.37	1.15	0.033	0.66	0.18	0.06	0.83	63.0
MK-35	105.4921	10.49890	5.1	9.1	16.8	0.51	5.58	2.41	1.17	0.037	0.74	0.27	0.12	0.88	62.3
MK-36	105.5078	10.46332	5.0	12.3	18.6	0.48	4.92	2.45	1.07	0.022	0.49	0.24	0.09	0.79	58.5
MK-37	105.4510	10.53349	4.6	8.4	15.4	0.40	5.45	2.34	1.08	0.033	0.67	0.18	0.04	0.86	65.1
MK-38	105.4103	10.53300	5.5	9.4	17.9	0.54	4.79	2.47	1.08	0.031	0.55	0.18	0.05	0.75	62.3
MK-40	105.4384	10.53296	4.9	10.7	18.9	0.61	4.61	2.62	1.17	0.029	0.56	0.24	0.07	0.76	59.7
MK-41	105.4269	10.53729	4.5	11.8	18.3	0.46	5.40	2.60	1.26	0.031	0.57	0.19	0.10	0.80	58.5
MK-42	105.4139	10.54031	4.8	11.1	15.4	0.58	5.09	2.31	1.13	0.031	0.67	0.19	0.12	0.76	62.6
MK-43	106.1629	10.15198	4.8	8.6	13.6	0.40	3.19	2.09	0.78	0.016	0.72	0.12	0.08	0.83	69.6
MK-44	106.1141	10.16194	4.7	11.9	19.0	0.42	3.89	2.51	0.97	0.012	0.57	0.10	0.10	0.91	59.7
MK-45	106.1052	10.16381	4.5	11.8	16.1	0.48	3.97	2.21	0.90	0.017	0.62	0.14	0.13	0.90	62.7
MK-46	106.0737	10.16444	4.0	11.4	15.5	0.39	2.63	2.29	0.77	0.016	0.67	0.12	0.19	0.89	65.1
MK-47	106.0812	10.16661	4.2	9.7	16.3	0.50	4.80	2.39	0.99	0.042	0.67	0.16	0.20	0.87	63.5
MK-48	105.0946	10.17084	4.7	11.8	15.2	0.43	2.87	2.17	0.72	0.009	0.72	0.11	0.13	0.89	64.9
MK-49	106.1047	10.18074	4.3	13.0	18.2	0.38	4.15	2.41	0.88	0.012	0.59	0.17	0.14	0.84	59.2
MK-51	105.3216	10.83619	5.4	6.7	12.1	0.43	4.62	1.89	0.87	0.034	0.63	0.15	0.04	0.72	71.8
MK-52	105.3270	10.84106	5.5	12.4	16.7	0.76	4.98	2.42	1.06	0.072	0.58	0.19	0.30	0.76	59.8
MK-53	105.3333	10.83933	4.6	11.6	17.3	0.49	5.13	2.51	1.13	0.026	0.58	0.15	0.17	0.78	60.1
MK-54	105.3181	10.82736	4.6	11.3	17.0	0.44	4.90	2.45	1.14	0.026	0.57	0.13	0.07	0.75	61.2
MK-55	105.3244	10.82386	4.9	10.4	18.7	0.54	5.56	2.67	1.22	0.036	0.52	0.16	0.09	0.78	59.3
MK-56	105.3239	10.82708	5.3	13.0	19.8	0.61	5.36	2.69	1.28	0.036	0.47	0.21	0.09	0.76	55.7
MK-57	105.3321	10.82444	5.7	8.1	15.6	0.49	5.44	2.26	0.99	0.057	0.61	0.12	0.04	0.78	65.5
MK-58	105.3343	10.81592	5.1	9.6	16.5	0.46	5.51	2.31	1.02	0.035	0.56	0.12	0.06	0.76	63.1
MK-59	105.3526	10.79633	6.8	9.2	14.7	1.27	4.44	2.28	1.02	0.048	0.58	0.22	0.07	0.64	65.6
MK-60	105.3582	10.77364	5.2	9.1	15.8	0.53	5.10	2.40	1.13	0.058	0.60	0.20	0.05	0.72	64.3

Table A2.1 (*cont.*) Coordinates of sampling locations in the Mekong River Delta area, pH-values and concentrations of main elements and LOI in paddy soils in wt. % (n = 78)

Sites	Coordinate		pH	LOI	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO	Na_2O	P_2O_5	S	TiO_2	SiO_2
	E	N													
MK-61	105.3770	10.52436	5.3	7.7	14.0	0.50	5.15	2.19	1.05	0.058	0.70	0.18	0.03	0.78	67.7
MK-62	105.3861	10.51619	5.4	8.4	14.6	0.52	4.29	2.08	0.92	0.037	0.58	0.21	0.04	0.74	67.5
MK-63	105.4013	10.50378	5.6	8.4	14.8	0.59	5.18	2.26	1.06	0.068	0.60	0.26	0.04	0.74	66.0
MK-64	105.3988	10.48869	3.8	9.9	18.1	0.30	4.93	2.48	1.05	0.016	0.58	0.12	0.16	0.82	61.6
MK-65	105.3840	10.43972	4.0	10.2	20.1	0.40	5.14	2.63	1.09	0.027	0.49	0.12	0.26	0.77	58.8
MK-66	105.3900	10.43422	3.7	9.2	19.5	0.53	5.38	2.65	1.13	0.034	0.52	0.10	0.34	0.79	59.9
MK-67	105.9468	9.877722	4.8	11.4	18.9	0.43	4.02	2.76	1.07	0.020	0.59	0.17	0.08	0.86	59.7
MK-68	105.9506	9.868500	5.1	12.9	18.5	0.46	3.52	2.71	1.05	0.024	0.60	0.19	0.09	0.86	59.1
MK-69	105.9633	9.862083	5.0	12.6	18.5	0.43	3.67	2.70	1.05	0.022	0.58	0.20	0.08	0.85	59.2
MK-70	105.9845	9.837694	5.1	12.0	19.3	0.47	5.57	2.73	1.18	0.042	0.55	0.19	0.08	0.83	57.1
MK-71	105.9907	9.832972	5.0	14.7	18.3	0.70	5.32	2.59	1.15	0.040	0.56	0.24	0.12	0.80	55.5
MK-72	106.0933	9.811639	5.4	11.8	13.6	0.65	4.78	2.13	0.79	0.021	0.69	0.28	0.09	0.76	64.4
MK-73	106.0785	9.825667	5.7	11.0	14.7	0.50	5.07	2.29	0.94	0.030	0.68	0.21	0.10	0.76	63.7
MK-74	106.0783	9.812667	4.9	12.3	13.7	0.96	4.80	2.15	0.80	0.021	0.70	0.29	0.12	0.74	63.4
MK-75	106.0711	9.846556	4.7	8.6	13.4	0.35	3.81	2.02	0.76	0.046	0.69	0.13	0.10	0.81	69.3
MK-76	105.6119	10.35236	4.3	14.4	19.5	0.49	3.64	2.19	0.89	0.016	0.43	0.18	0.16	0.78	57.3
MK-77	105.6144	10.35535	4.4	10.5	15.9	0.48	4.78	2.26	1.02	0.025	0.61	0.16	0.11	0.78	63.4
MK-78	105.6179	10.36672	4.8	10.8	18.7	0.48	4.57	2.44	1.04	0.026	0.51	0.18	0.08	0.81	60.4
MK-79	105.6466	10.38142	4.4	15.0	20.2	0.46	5.24	2.40	1.08	0.018	0.40	0.16	0.18	0.69	54.1
MK-80	105.7149	10.47660	4.5	14.2	17.8	0.44	3.82	2.16	0.87	0.020	0.41	0.12	0.13	0.79	59.2
MK-81	105.7232	10.49193	4.2	12.8	17.1	0.45	5.37	2.23	0.91	0.029	0.50	0.16	0.22	0.79	59.5
MK-82	105.8007	10.48096	4.0	14.5	15.9	0.50	3.15	2.08	0.70	0.019	0.49	0.30	0.43	0.84	61.1

Table A2.2 Concentrations of trace elements in paddy soils in the Mekong River Delta area in mg kg^{-1} (n = 78)

Sites	As	Ba	Bi	Cd	Ce	Co	Cs	Cu	Hf	La	Li	Mo	Ni	Pb	Rb	Sb	Sn	Sr	Th	Tl	U	V	Zn	Zr
MK-1	13.4	416	0.39	0.33	73	13.9	10.6	31	3.89	37	45	0.77	39	25	120	1.94	3.9	88	14.4	0.64	4.0	107	103	145
MK-2	13.1	463	0.48	0.34	85	14.0	14.3	38	4.09	43	58	0.85	44	31	143	2.33	4.7	87	17.5	0.81	4.9	138	98	151
MK-3	12.3	411	0.46	0.36	86	15.4	10.2	33	4.55	42	47	0.67	37	30	120	2.69	4.5	87	16.6	0.66	4.6	114	93	167
MK-4	12.5	370	0.36	0.33	74	13.8	8.0	26	4.84	37	37	0.57	30	24	103	2.26	3.8	84	14.7	0.55	3.8	92	73	174
MK-5	15.8	419	0.42	0.33	85	17.2	10.3	30	4.65	41	47	0.77	38	29	123	2.35	4.3	89	16.1	0.66	4.2	113	98	170
MK-6	13.6	366	0.34	0.29	74	14.0	8.1	25	4.95	37	38	0.60	32	23	99	1.98	3.6	87	14.3	0.54	3.6	91	74	180
MK-7	12.8	390	0.36	0.33	76	13.4	9.4	33	4.70	38	43	0.66	34	26	109	2.01	3.8	85	14.8	0.60	4.3	106	95	171
MK-8	28.9	417	0.37	0.38	85	19.9	9.2	29	4.51	39	42	0.82	35	29	110	2.05	4.0	85	14.5	0.58	4.5	107	87	165
MK-9	25.2	465	0.44	0.31	82	15.4	12.7	34	4.00	41	53	0.77	41	29	137	2.07	4.6	88	16.0	0.74	4.8	126	98	149
MK-10	13.0	457	0.52	0.34	83	15.1	14.2	36	3.93	42	58	0.78	43	32	145	2.54	5.2	84	17.3	0.83	4.9	131	112	146
MK-11	9.5	346	0.29	0.26	69	12.2	7.2	24	4.47	34	35	0.49	27	22	94	1.92	3.5	82	13.0	0.50	3.9	84	73	165
MK-12	16.0	403	0.40	0.32	81	15.6	9.0	28	4.40	40	41	0.71	34	25	113	2.33	4.2	82	15.5	0.60	3.9	101	79	163
MK-13	14.5	420	0.45	0.33	86	16.5	11.2	33	4.54	43	48	0.69	39	30	131	2.37	4.5	83	16.7	0.70	4.9	117	100	167
MK-14	9.1	353	0.34	0.29	72	12.0	8.5	29	5.09	36	39	0.51	29	190	109	6.45	4.4	78	14.2	0.55	4.0	92	81	188
MK-15	13.5	371	0.34	0.30	75	14.3	8.0	26	4.81	37	39	0.60	31	24	101	2.04	3.6	84	14.3	0.55	4.2	94	73	175
MK-16	13.6	375	0.35	0.29	77	14.8	8.1	27	4.02	38	39	0.52	31	24	104	2.14	3.6	90	14.1	0.55	4.1	95	76	147
MK-17	15.3	368	0.38	0.28	74	14.0	8.4	27	3.97	36	39	0.64	31	24	103	2.11	3.8	86	14.3	0.56	4.1	95	77	145
MK-18	15.7	423	0.49	0.33	86	15.4	12.0	35	3.90	43	50	0.82	41	31	136	2.67	4.7	83	16.8	0.74	4.8	121	104	144
MK-19	12.8	380	0.38	0.36	78	14.9	8.5	28	4.15	38	38	0.58	33	25	106	2.41	3.9	84	14.8	0.58	4.6	94	82	152
MK-20	13.1	398	0.39	0.32	81	16.4	9.4	30	4.14	40	43	2.16	42	26	115	2.17	3.9	82	14.9	0.62	4.4	107	89	154
MK-21	10.7	371	0.38	0.31	76	12.2	9.6	29	4.16	38	43	0.75	32	25	108	2.05	3.9	78	14.8	0.61	4.3	102	85	152
MK-22	11.2	406	0.41	0.26	81	12.6	12.4	31	4.05	41	52	0.99	38	26	123	2.14	4.2	80	15.8	0.72	5.2	118	90	148
MK-23	10.2	405	0.40	0.32	73	12.9	12.4	33	3.61	37	53	1.08	39	27	111	2.15	4.1	80	14.8	0.70	5.2	117	100	131
MK-24	11.8	421	0.41	0.36	79	13.4	12.8	34	3.80	40	53	0.98	38	26	121	2.03	4.2	82	15.9	0.72	5.0	121	99	141
MK-25	8.5	394	0.37	0.26	74	11.8	10.4	28	3.92	37	45	0.67	33	24	108	1.99	3.9	82	14.3	0.63	4.4	103	92	142
MK-26	12.5	311	0.47	0.17	79	14.1	12.1	27	3.63	39	63	1.15	42	27	136	1.30	4.6	77	16.4	0.67	4.7	119	98	136
MK-27	10.5	313	0.38	0.19	81	13.8	9.4	20	4.57	40	54	0.98	36	23	116	1.07	3.9	77	15.4	0.58	4.9	100	81	164
MK-30	12.0	447	0.44	0.24	80	13.6	13.0	30	3.87	40	56	0.85	39	28	134	2.22	4.4	81	15.9	0.77	4.5	126	96	145
MK-31	14.9	422	0.44	0.32	81	15.2	11.1	33	3.85	40	46	0.75	38	28	129	2.34	4.2	83	15.5	0.67	4.2	116	97	145
MK-32	11.6	414	0.46	0.31	86	13.9	11.0	32	4.02	42	47	0.62	37	29	130	2.47	4.3	81	16.0	0.68	5.0	119	98	148
MK-33	10.4	426	0.44	0.28	86	13.1	11.9	34	3.96	44	50	0.72	38	28	133	2.24	4.6	84	16.1	0.69	4.8	125	102	147
MK-34	11.5	413	0.38	0.24	78	13.2	10.8	31	4.15	40	46	0.75	36	26	123	1.94	3.9	86	15.1	0.64	4.3	114	91	151
MK-35	10.9	410	0.40	0.24	85	14.4	11.2	29	4.30	43	48	0.61	37	27	126	1.90	4.7	87	16.0	0.67	4.6	115	92	158
MK-36	13.0	408	0.44	0.26	108	14.2	12.8	34	3.90	53	62	1.08	44	29	128	2.12	4.4	81	15.9	0.72	5.2	126	118	145
MK-37	11.4	389	0.37	0.29	81	13.8	9.8	30	4.36	40	43	0.63	34	25	117	1.88	3.8	81	14.9	0.60	4.3	108	87	161
MK-38	11.6	434	0.39	0.23	76	13.0	12.7	29	3.89	39	52	0.85	37	26	132	1.96	4.7	84	15.4	0.72	4.9	120	90	143
MK-40	10.9	432	0.43	0.32	79	13.7	13.2	36	3.89	41	54	0.84	41	28	136	2.13	4.1	86	15.7	0.74	4.7	126	102	147
MK-41	13.3	433	0.47	0.36	83	14.8	12.5	35	3.80	42	52	0.85	41	30	136	2.49	4.4	82	16.2	0.74	4.5	124	106	142
MK-42	14.0	386	0.42	0.37	77	13.4	10.3	32	4.13	39	43	0.90	37	28	119	2.57	4.3	79	15.1	0.64	4.2	107	94	152

Table A2.2 (*Cont.*) Concentrations of trace elements in paddy soils in the Mekong River Delta area in mg kg^{-1} (n = 78)

Sites	As	Ba	Bi	Cd	Ce	Co	Cs	Cu	Hf	La	Li	Mo	Ni	Pb	Rb	Sb	Sn	Sr	Th	Tl	U	V	Zn	Zr
MK-43	9.0	378	0.32	0.18	75	8.7	8.5	24	4.42	38	43	0.93	26	22	102	1.55	3.4	82	13.9	0.54	4.0	92	62	162
MK-44	10.4	409	0.41	0.16	82	8.8	12.9	27	4.08	42	59	1.01	32	28	129	1.70	4.3	87	16.1	0.71	4.6	122	74	152
MK-45	11.0	373	0.38	0.22	87	10.5	10.7	27	4.30	43	51	0.81	31	25	114	1.78	4.1	87	16.1	0.62	5.0	110	79	158
MK-46	8.4	360	0.34	0.18	74	6.7	10.4	25	4.29	38	50	1.31	24	21	120	1.40	4.0	83	14.4	0.59	4.1	98	53	157
MK-47	18.6	382	0.38	0.21	77	11.7	10.8	25	4.21	39	52	1.07	31	25	121	1.61	4.0	87	15.2	0.62	4.3	107	72	154
MK-48	9.2	357	0.40	0.16	73	5.6	10.2	28	4.09	37	46	1.53	23	24	115	1.58	4.0	81	14.7	0.60	4.6	104	51	149
MK-49	11.0	395	0.39	0.16	78	7.7	12.7	27	3.67	40	60	1.20	30	27	129	1.64	4.3	79	14.9	0.69	4.6	116	69	137
MK-51	10.0	325	0.31	0.24	70	12.1	7.8	24	3.88	35	36	0.60	27	22	95	1.86	3.2	71	12.6	0.50	3.6	86	72	144
MK-52	13.1	407	0.42	0.30	82	20.6	12.2	35	3.76	42	49	1.07	44	27	136	2.35	4.4	88	15.3	0.69	4.4	116	109	141
MK-53	12.7	415	0.44	0.29	81	13.4	12.2	35	3.81	41	50	1.11	39	29	135	2.32	4.3	83	15.8	0.72	4.5	119	99	141
MK-54	11.0	402	0.45	0.30	83	14.0	12.2	36	3.83	42	51	0.92	40	29	134	2.37	4.3	79	15.6	0.72	4.4	116	104	143
MK-55	13.7	447	0.48	0.31	93	16.7	13.5	38	3.50	46	57	1.12	47	31	145	2.58	4.5	85	16.4	0.76	4.7	129	115	133
MK-56	13.4	456	0.49	0.34	95	17.1	14.3	41	3.45	47	61	1.12	50	32	147	2.62	4.7	88	16.4	0.80	4.9	134	120	132
MK-57	15.0	396	0.39	0.32	90	16.7	10.7	32	3.75	44	46	0.93	39	27	120	2.07	3.9	84	14.9	0.63	4.4	110	107	142
MK-58	14.2	400	0.41	0.27	91	15.1	11.5	34	3.72	45	49	0.98	40	28	121	2.22	4.0	80	15.2	0.67	4.5	119	101	139
MK-59	10.4	406	0.33	0.24	68	12.4	10.4	28	3.09	35	43	0.68	34	24	116	1.73	3.5	89	12.8	0.63	3.6	100	86	115
MK-60	12.6	414	0.38	0.28	76	14.1	11.2	32	3.48	39	46	0.67	37	26	128	1.98	4.2	82	14.4	0.67	3.9	108	93	131
MK-61	13.5	378	0.37	0.31	78	13.9	8.8	29	4.10	39	38	0.63	32	26	110	2.20	3.9	79	14.7	0.57	4.2	99	84	153
MK-62	10.6	377	0.34	0.28	75	13.0	9.9	25	4.70	38	43	0.63	32	23	110	1.83	3.6	75	14.2	0.59	4.3	99	86	179
MK-63	13.9	393	0.39	0.43	78	15.4	9.7	29	4.42	39	42	0.67	34	26	113	2.00	4.0	79	15.0	0.61	4.4	100	91	168
MK-64	14.5	406	0.43	0.23	79	10.8	13.0	29	4.50	41	57	0.99	34	28	129	1.93	4.7	80	14.3	0.71	4.3	118	87	171
MK-65	11.5	426	0.40	0.34	103	20.1	14.5	28	4.02	51	69	0.89	48	27	143	1.92	4.3	81	15.4	0.78	4.7	121	134	153
MK-66	14.4	443	0.42	0.29	90	19.0	14.1	33	4.25	46	64	0.87	45	29	140	1.99	4.4	85	15.9	0.78	4.6	123	118	161
MK-67	9.8	383	0.42	0.17	84	9.1	13.3	27	4.43	43	60	0.96	32	26	148	1.43	4.4	87	16.6	0.72	4.3	115	78	166
MK-68	8.3	378	0.41	0.20	86	8.8	13.3	28	4.31	44	59	1.01	32	26	150	1.41	4.3	88	16.6	0.70	4.4	114	80	161
MK-69	8.5	373	0.40	0.18	85	8.9	13.3	27	4.27	44	61	0.93	32	26	150	1.43	4.3	87	16.3	0.71	4.4	114	77	163
MK-70	13.8	404	0.43	0.17	85	10.5	13.8	28	4.15	43	66	0.95	35	28	149	1.71	4.5	88	16.2	0.74	4.2	122	79	158
MK-71	12.5	397	0.42	0.19	84	10.1	13.2	28	4.10	42	61	0.92	34	28	142	1.73	4.7	92	15.6	0.70	4.1	118	79	154
MK-72	12.8	290	0.38	0.21	75	8.3	9.3	29	5.26	38	43	1.69	27	25	113	1.34	3.9	104	15.6	0.54	4.1	94	74	197
MK-73	14.0	296	0.38	0.20	75	10.4	10.2	25	4.93	38	47	1.47	31	24	120	1.32	3.9	101	15.4	0.55	4.0	98	73	188
MK-74	12.0	283	0.36	0.20	70	7.9	9.2	26	5.10	35	43	1.50	26	23	111	1.29	3.7	108	14.5	0.52	4.0	94	70	192
MK-75	8.9	293	0.35	0.22	80	10.7	8.8	23	4.84	40	43	0.73	27	25	108	1.38	4.2	75	15.0	0.53	4.2	90	66	179
MK-76	11.2	421	0.45	0.23	92	10.5	14.5	36	4.15	45	76	1.72	38	30	122	2.35	4.4	81	16.2	0.75	4.9	125	83	157
MK-77	11.4	391	0.38	0.36	79	15.2	11.2	34	3.96	40	50	0.91	38	27	117	1.94	4.1	78	14.6	0.64	4.1	106	118	148
MK-78	12.2	430	0.42	0.25	82	13.6	13.2	32	3.91	42	59	1.19	38	28	126	2.18	4.3	80	15.7	0.72	4.7	121	103	147
MK-79	16.4	460	0.50	0.32	91	14.8	14.8	43	3.68	46	69	2.63	50	33	130	2.83	4.4	84	16.1	0.79	5.3	139	110	141
MK-80	11.1	384	0.39	0.22	84	11.5	13.3	30	3.83	43	60	1.25	36	27	120	1.93	4.2	75	15.1	0.71	4.6	115	85	145
MK-81	17.1	355	0.41	0.29	95	14.9	12.1	29	4.06	46	58	1.44	41	27	116	2.13	4.1	76	16.2	0.66	4.8	118	101	154
MK-82	10.2	345	0.34	0.20	91	8.4	11.1	22	4.19	45	59	1.31	31	25	111	1.52	3.9	89	14.2	0.62	4.3	99	69	157

Table A2.3 Concentrations of elements in rice grains in the Mekong River Delta area in mg kg^{-1} (n = 78)

Sites	Al	Ca	Fe	K	Mg	Mn	Na	P	S	Ti	As	Ba	Bi	Cd	Ce	Co	Cr	Cs	Cu
MK-1	<0.8	73	8.5	1817	1128	15.1	4.1	2598	770	<0.05	0.10	0.40	0.0003	0.003	<0.0006	0.009	<0.1	0.032	2.74
MK-2	<0.8	87	11.2	2415	1488	22.1	9.0	3570	1024	<0.05	0.15	0.45	0.0006	0.064	0.0006	0.012	<0.1	0.047	2.72
MK-3	<0.8	78	8.8	2257	1323	21.1	5.8	3210	814	<0.05	0.11	0.71	0.0004	0.021	<0.0006	0.014	<0.1	0.022	3.09
MK-4	1.4	72	9.6	2595	1342	24.7	5.6	3546	866	<0.05	0.11	0.54	0.0003	0.026	0.0006	0.022	<0.1	0.030	4.96
MK-5	<0.8	71	8.4	2483	1362	18.6	5.1	3348	782	<0.05	0.13	0.56	0.0004	0.020	<0.0006	0.021	<0.1	0.022	3.19
MK-6	2.2	68	8.7	2629	1336	22.1	5.8	3310	793	0.07	0.11	0.60	0.0002	0.026	0.0013	0.027	<0.1	0.022	10.21
MK-7	<0.8	79	10.1	2690	1473	18.7	12.4	3576	879	0.09	0.18	0.62	0.0004	0.005	0.0007	0.011	<0.1	0.015	3.42
MK-8	<0.8	85	11.6	2666	1382	28.6	12.1	3511	938	0.06	0.20	1.48	0.0015	0.038	0.0010	0.031	<0.1	0.013	4.57
MK-9	<0.8	66	9.3	2264	1167	23.1	4.4	2857	812	0.10	0.23	0.29	<0.0002	0.007	<0.0006	0.014	<0.1	0.004	3.99
MK-10	<0.8	86	9.5	2336	1121	14.0	4.4	2967	737	0.17	0.35	0.25	0.0003	0.003	0.0006	0.012	<0.1	0.013	1.09
MK-11	<0.8	82	7.8	2320	1149	22.2	4.0	2925	770	0.41	0.31	0.29	0.0006	0.047	<0.0006	0.019	<0.1	0.019	2.72
MK-12	<0.8	73	7.3	2140	1145	19.4	3.4	2758	624	<0.05	0.42	0.42	0.0003	0.003	<0.0006	0.023	<0.1	0.028	2.06
MK-13	<0.8	92	11.0	2574	1251	20.9	4.8	3114	746	<0.05	0.27	0.31	0.0004	0.008	<0.0006	0.023	<0.1	0.040	1.47
MK-14	<0.8	81	8.6	2398	1226	20.2	3.3	3118	882	<0.05	0.31	0.37	<0.0002	0.007	<0.0006	0.018	<0.1	0.007	1.67
MK-15	<0.8	72	7.8	2226	1084	18.6	5.3	2721	831	<0.05	0.27	0.34	0.0005	0.021	<0.0006	0.023	<0.1	0.017	2.59
MK-16	2.2	76	6.6	2082	1011	14.7	4.4	2469	784	<0.05	0.17	0.72	0.0003	0.025	<0.0006	0.020	<0.1	0.045	2.76
MK-17	<0.8	88	8.9	2551	1223	24.9	4.6	3116	959	<0.05	0.19	0.38	0.0004	0.055	<0.0006	0.021	<0.1	0.042	6.06
MK-18	<0.8	89	8.3	2334	1251	21.1	3.3	3173	895	<0.05	0.24	0.24	0.0002	0.035	<0.0006	0.017	<0.1	0.017	2.37
MK-19	<0.8	103	8.4	2374	1141	20.8	4.7	3002	806	<0.05	0.56	0.26	<0.0002	0.002	<0.0006	0.031	<0.1	0.055	2.36
MK-20	<0.8	90	10.8	2561	1278	19.5	4.4	3278	961	<0.05	0.29	0.56	0.0004	0.009	<0.0006	0.015	<0.1	0.006	1.67
MK-21	<0.8	110	9.9	2874	1275	23.7	4.8	3521	956	<0.05	0.19	0.56	0.0014	0.070	0.0012	0.025	<0.1	0.039	2.15
MK-22	<0.8	113	10.5	2998	1198	26.0	6.4	3356	996	<0.05	0.12	1.01	<0.0002	0.070	<0.0006	0.015	<0.1	0.030	3.26
MK-23	<0.8	102	9.9	2694	1198	14.6	4.8	3197	950	<0.05	0.13	0.88	0.0003	0.036	<0.00062	0.008	<0.1	0.042	2.60
MK-24	<0.8	104	9.9	2786	1417	20.5	5.5	3686	1033	<0.05	0.17	0.77	0.0006	0.053	<0.0006	0.016	<0.1	0.059	3.27
MK-25	2.2	113	10.5	3016	1282	24.9	5.7	3518	1044	0.08	0.13	0.73	0.0004	0.187	<0.0006	0.038	<0.1	0.038	3.79
MK-26	3.4	81	8.9	2241	1184	15.9	5.6	2872	695	<0.05	0.17	0.39	0.0010	0.011	<0.0006	0.016	<0.1	0.014	1.88
MK-27	<0.8	90	10.2	2584	1381	28.1	5.5	3345	921	<0.05	0.15	0.73	0.0013	0.021	<0.00062	0.026	<0.1	0.007	2.61
MK-30	<0.8	100	10.8	3026	1510	20.9	5.5	3926	1113	<0.05	0.23	1.59	0.0005	0.005	<0.0006	0.011	<0.1	0.044	3.46
MK-31	<0.8	76	9.4	2355	1312	22.7	5.2	3299	898	<0.05	0.28	0.68	0.0004	0.012	<0.0006	0.021	<0.1	0.008	3.36
MK-32	2.2	84	11.6	2543	1361	18.1	5.3	3419	962	0.08	0.26	0.92	0.0010	0.004	0.0012	0.024	<0.1	0.021	2.60
MK-33	2.4	95	10.4	2656	1438	18.0	4.9	3419	1002	<0.05	0.24	0.63	0.0003	0.014	0.0010	0.021	<0.1	0.022	2.08
MK-34	<0.8	83	10.9	2152	1084	25.0	4.7	2669	948	<0.05	0.11	0.73	<0.0002	0.109	<0.0006	0.025	<0.1	0.019	4.07
MK-35	1.1	78	12.1	2458	1310	20.9	29.1	3242	980	0.09	0.16	0.30	0.0019	0.014	0.0013	0.017	<0.1	0.024	2.49
MK-36	<0.8	97	11.0	2523	1266	24.1	6.1	3174	1102	<0.05	0.08	0.26	<0.0002	0.065	<0.0006	0.029	<0.1	0.040	5.75
MK-37	1.4	90	12.3	2750	1362	23.7	4.0	3347	990	0.07	0.14	1.21	0.0012	0.087	0.0015	0.039	<0.1	0.013	3.72
MK-38	<0.8	74	8.3	2123	1012	13.1	4.2	2587	740	<0.05	0.18	0.33	0.0003	0.019	<0.0006	0.012	<0.1	0.005	2.56
MK-40	1.3	93	8.3	2567	1232	23.2	4.6	3130	709	0.13	0.25	0.49	0.0005	0.062	0.0007	0.020	0.16	0.029	2.48
MK-41	4.0	85	13.0	2584	1477	21.4	6.5	3691	875	0.13	0.22	0.38	0.0007	0.018	<0.0006	0.032	NA	0.012	1.86
MK-42	1.7	80	9.0	2334	1245	21.3	6.2	3056	717	<0.05	0.17	0.34	0.0004	0.042	<0.0006	0.025	0.28	0.011	3.61

Table A2.3 (*cont.*) Concentrations of elements in rice grains in the Mekong River Delta area in mg kg^{-1} (n = 78)

Sites	Al	Ca	Fe	K	Mg	Mn	Na	P	S	Ti	As	Ba	Bi	Cd	Ce	Co	Cr	Cs	Cu
MK-43	1.3	87	10.1	2793	1274	24.3	7.1	3351	821	<0.05	0.13	0.60	0.0004	0.057	<0.0006	0.054	0.64	0.056	3.11
MK-44	1.6	92	10.9	2202	1115	14.1	9.3	2850	791	<0.05	0.15	0.48	<0.0002	0.030	<0.0006	0.021	0.23	0.071	2.60
MK-45	1.2	97	11.5	2871	1436	17.8	8.9	3761	931	<0.05	0.20	0.21	<0.0002	0.025	<0.0006	0.012	0.46	0.031	2.96
MK-46	<0.8	113	9.9	2714	1388	14.5	9.0	3608	954	<0.05	0.22	0.19	<0.0002	0.003	<0.0006	0.010	<0.1	0.037	1.95
MK-47	5.2	82	16.1	2615	1306	24.7	6.3	3427	796	<0.05	0.25	0.32	0.0002	0.010	<0.0006	0.019	NA	0.039	1.28
MK-48	6.3	101	17.4	2383	1234	15.7	9.0	3147	873	<0.05	0.17	0.21	0.0005	0.049	<0.0006	0.046	NA	0.116	3.87
MK-49	3.4	96	15.4	2482	1428	19.7	6.9	3621	907	0.13	0.16	0.26	0.0009	0.036	0.0014	0.023	<0.1	0.032	3.77
MK-51	<0.8	108	10.7	2505	1337	19.8	10.1	3276	790	0.30	0.37	0.67	0.0004	0.003	0.0006	0.023	0.18	0.036	1.41
MK-52	1.2	89	11.7	2798	1270	18.4	9.4	3249	900	0.06	0.12	0.08	0.0003	0.014	<0.0006	0.077	<0.1	0.004	2.88
MK-53	<0.8	83	8.9	2546	1202	17.1	9.2	3116	789	<0.05	0.22	0.12	0.0002	0.042	<0.0006	0.024	<0.1	0.012	3.80
MK-54	0.9	89	9.9	2557	1294	23.0	6.7	3149	758	<0.05	0.18	0.77	0.0003	0.038	0.0010	0.031	0.29	0.055	3.41
MK-55	19.4	92	12.3	2851	1406	21.9	7.3	3552	864	<0.05	0.25	0.82	0.0004	0.003	0.0008	0.028	0.18	0.018	6.92
MK-56	1.5	81	13.2	2376	1239	18.1	6.5	3052	827	<0.05	0.14	0.47	0.0003	0.046	<0.0006	0.023	0.64	0.012	3.14
MK-57	<0.8	86	11.7	2520	1316	20.9	12.1	3274	754	0.09	0.19	1.02	0.0004	0.023	0.0007	0.018	<0.1	0.010	3.17
MK-58	<0.8	86	11.1	2762	1418	24.6	6.5	3500	928	<0.05	0.14	1.35	0.0004	0.013	<0.0006	0.019	<0.1	0.013	3.89
MK-59	<0.8	97	9.8	2339	1169	14.6	4.4	2979	832	0.09	0.11	0.16	0.0003	0.010	<0.0006	0.018	<0.1	0.010	3.62
MK-60	<0.8	90	10.9	2830	1340	23.2	6.4	3511	845	<0.05	0.18	0.69	0.0008	0.055	<0.0006	0.020	0.57	0.020	2.95
MK-61	<0.8	101	11.4	2937	1191	26.3	6.0	3316	883	<0.05	0.13	0.98	<0.0002	0.114	<0.0006	0.028	0.30	0.033	3.68
MK-62	6.5	101	10.5	2910	1282	23.4	5.3	3490	857	<0.05	0.13	0.83	0.0003	0.054	<0.0006	0.013	0.23	0.029	2.61
MK-63	4.6	92	NA	2655	1294	20.3	5.0	3369	874	<0.05	0.24	0.34	0.0006	0.049	0.0007	0.063	NA	0.044	3.11
MK-64	<0.8	96	10.8	2776	1475	24.5	6.3	3809	1074	<0.05	0.09	0.09	<0.0002	0.098	0.0007	0.115	0.13	0.051	4.94
MK-65	0.8	77	9.3	2577	1226	15.0	6.1	3198	775	<0.05	0.13	0.47	<0.0002	0.003	0.0009	0.011	0.22	0.046	1.39
MK-66	1.9	84	11.9	2956	1306	15.5	8.6	3470	844	0.06	0.21	0.68	0.0005	0.001	0.0008	0.015	0.31	0.050	1.38
MK-67	<0.8	81	10.1	2833	1212	25.7	14.3	3127	881	<0.05	0.11	0.27	<0.0002	0.162	<0.0006	0.025	0.20	0.002	5.34
MK-68	<0.8	85	9.6	2862	1215	27.0	12.1	3104	851	<0.05	0.12	0.44	<0.0002	0.177	<0.0006	0.025	0.28	0.002	4.36
MK-69	1.0	77	11.0	2784	1188	21.5	17.2	3007	795	<0.05	0.08	0.50	0.0004	0.107	0.0012	0.013	0.20	0.002	5.62
MK-70	0.9	74	9.9	3068	1385	23.5	25.9	3339	760	<0.05	0.10	0.34	<0.0002	0.027	0.0018	0.010	<0.1	0.009	2.28
MK-71	1.3	78	11.5	3462	1562	26.9	22.8	3915	905	0.07	0.09	0.42	<0.0002	0.036	0.0010	0.011	<0.1	0.010	2.58
MK-72	1.0	77	10.9	2784	1275	16.6	12.7	3150	843	<0.05	0.10	0.08	<0.0002	0.024	0.0006	0.017	<0.1	0.002	4.19
MK-73	<0.8	78	9.7	2800	1285	22.5	11.1	3334	786	<0.05	0.08	0.13	<0.0002	0.030	<0.0006	0.026	<0.1	0.005	4.13
MK-74	<0.8	89	10.6	2874	1379	25.4	14.6	3612	840	0.22	0.12	0.11	0.0005	0.016	0.0010	0.024	<0.1	0.003	4.34
MK-75	<0.8	90	12.2	2694	1541	24.3	6.2	3813	1021	<0.05	0.12	0.25	0.0004	0.015	<0.0006	0.030	<0.1	0.011	3.01
MK-76	<0.8	82	8.4	2450	1282	15.6	7.5	3188	1029	<0.05	0.14	0.42	<0.0002	0.009	<0.0006	0.019	<0.1	0.036	3.50
MK-77	6.0	78	10.3	2668	1461	14.8	6.3	3625	1060	<0.05	0.41	0.22	<0.0002	0.023	<0.0006	0.034	<0.1	0.072	2.31
MK-78	<0.8	85	8.8	2802	1395	16.4	6.4	3610	1017	<0.05	0.17	1.17	0.0003	0.018	<0.0006	0.041	<0.1	0.032	4.00
MK-79	1.1	85	9.8	2420	1248	18.4	11.8	3051	1006	0.05	0.11	0.43	<0.0002	0.037	<0.0006	0.047	<0.1	0.146	3.55
MK-80	<0.8	74	8.2	2318	1132	25.1	5.5	2768	956	<0.05	0.08	0.46	<0.0002	0.070	<0.0006	0.037	<0.1	0.044	4.47
MK-81	<0.8	71	9.7	2550	1319	16.9	5.2	3283	897	0.09	0.16	0.17	<0.0002	0.013	0.0007	0.022	<0.1	0.038	1.74
MK-82	6.8	98	10.5	3108	1339	18.5	4.9	3343	1009	<0.05	0.10	0.05	<0.0002	0.023	<0.0006	0.072	<0.1	0.012	3.48

< lower than detection limits, NA: not analyzed

Table A2.3 *(cont.)* Concentrations of elements in rice grains in the Mekong River Delta area in mg kg^{-1} (n = 78)

Sites	Hf	La	Li	Mo	Ni	Pb	Rb	Sb	Sn	Sr	Th	Tl	U	V	Zn	Zr
MK-1	<0.0002	<0.0003	<0.006	0.41	0.09	0.16	16.1	0.0007	<0.06	0.23	<0.0002	<0.0002	<0.0001	<0.008	17.4	<0.007
MK-2	<0.0002	0.0003	<0.006	1.02	0.15	0.33	21.1	0.0026	<0.06	0.30	<0.0002	<0.0002	<0.0001	<0.008	19.5	<0.007
MK-3	<0.0002	<0.0003	<0.006	0.32	0.21	0.12	11.9	<0.0006	0.07	0.33	<0.0002	<0.0002	<0.0001	<0.008	15.8	<0.007
MK-4	<0.0002	0.0003	<0.006	0.44	0.32	0.37	15.5	0.0006	<0.06	0.27	<0.0002	<0.0002	<0.0001	0.024	21.1	<0.007
MK-5	<0.0002	<0.0003	<0.006	0.30	0.18	0.15	12.8	<0.0006	<0.06	0.28	<0.0002	<0.0002	<0.0001	<0.008	15.0	<0.007
MK-6	<0.0002	0.0010	<0.006	0.32	0.26	0.47	13.6	0.0006	<0.06	0.27	<0.0002	<0.0002	<0.0001	0.013	19.8	0.007
MK-7	<0.0002	0.0003	<0.006	0.60	0.07	0.17	9.7	<0.0006	<0.06	0.28	0.0002	<0.0002	<0.0001	0.019	17.4	<0.007
MK-8	<0.0002	0.0005	0.006	0.35	0.39	0.28	6.9	<0.0006	<0.06	0.38	<0.0002	<0.0002	<0.0001	<0.008	20.5	<0.007
MK-9	0.0007	<0.0003	<0.006	0.48	0.13	0.11	2.7	<0.0006	<0.06	0.22	<0.0002	<0.0002	<0.0001	0.013	15.0	0.027
MK-10	<0.0002	0.0003	<0.006	0.29	0.03	0.23	5.6	<0.0006	<0.06	0.23	<0.0002	<0.0002	<0.0001	0.012	20.5	<0.007
MK-11	<0.0002	<0.0003	<0.006	0.44	0.30	0.09	9.6	<0.0006	<0.06	0.26	<0.0002	<0.0002	<0.0001	<0.008	18.4	<0.007
MK-12	<0.0002	<0.0003	<0.006	0.42	0.07	0.21	11.9	<0.0006	0.07	0.25	<0.0002	<0.0002	<0.0001	<0.008	16.1	<0.007
MK-13	<0.0002	<0.0003	<0.006	0.40	0.08	0.31	19.2	0.0011	<0.06	0.31	<0.0002	<0.0002	<0.0001	<0.008	22.6	<0.007
MK-14	<0.0002	<0.0003	<0.006	0.40	0.11	0.12	5.2	<0.0006	0.08	0.28	<0.0002	<0.0002	<0.0001	<0.008	19.0	<0.007
MK-15	<0.0002	<0.0003	<0.006	0.35	0.15	0.12	6.6	<0.0006	<0.06	0.24	<0.0002	<0.0002	<0.0001	<0.008	17.4	<0.007
MK-16	<0.0002	<0.0003	<0.006	0.32	0.26	0.03	14.6	<0.0006	<0.06	0.32	<0.0002	<0.0002	<0.0001	<0.008	15.9	<0.007
MK-17	<0.0002	<0.0003	<0.006	0.28	0.59	0.16	17.2	<0.0006	<0.06	0.31	<0.0002	<0.0002	<0.0001	0.015	21.3	<0.007
MK-18	<0.0002	<0.0003	<0.006	0.39	0.21	0.06	6.0	<0.0006	<0.06	0.28	<0.0002	<0.0002	<0.0001	<0.008	21.1	<0.007
MK-19	<0.0002	<0.0003	0.006	0.60	0.06	0.04	18.5	<0.0006	<0.06	0.38	<0.0002	<0.0002	<0.0001	<0.008	17.6	<0.007
MK-20	<0.0002	0.0004	<0.006	0.38	0.12	0.27	4.3	<0.0006	0.07	0.38	<0.0002	<0.0002	<0.0001	<0.008	18.8	<0.007
MK-21	<0.0002	0.0007	<0.006	0.41	0.20	0.29	16.1	0.0016	<0.06	0.44	<0.0002	<0.0002	<0.0001	<0.008	20.8	<0.007
MK-22	<0.0002	<0.0003	<0.006	0.60	0.23	0.07	17.3	<0.0006	<0.06	0.53	<0.0002	<0.0002	<0.0001	<0.008	21.1	<0.007
MK-23	<0.0002	<0.0003	<0.006	0.47	0.12	0.08	19.1	<0.0006	0.06	0.49	<0.0002	<0.0002	<0.0001	<0.008	18.9	<0.007
MK-24	<0.0002	<0.0003	<0.006	0.50	0.34	0.03	18.4	<0.0006	<0.06	0.39	<0.0002	<0.0002	<0.0001	<0.008	20.7	<0.007
MK-25	<0.0002	<0.0003	<0.006	0.41	0.47	0.08	12.0	0.0006	<0.06	0.47	<0.0002	<0.0002	<0.0001	<0.008	23.3	<0.007
MK-26	<0.0002	<0.0003	<0.006	0.41	0.16	0.05	8.3	<0.0006	<0.06	0.48	<0.0002	<0.0002	<0.0001	<0.008	17.2	<0.007
MK-27	<0.0002	<0.0003	0.006	0.33	0.32	0.03	5.7	<0.0006	<0.06	0.48	<0.0002	<0.0002	<0.0001	0.013	22.2	<0.007
MK-30	<0.0002	<0.0003	<0.006	0.33	0.28	0.10	16.1	<0.0006	0.10	0.35	<0.0002	<0.0002	<0.0001	<0.008	20.3	<0.007
MK-31	<0.0002	<0.0003	<0.006	0.47	0.15	0.04	5.9	<0.0006	<0.06	0.31	<0.0002	<0.0002	<0.0001	<0.008	18.6	<0.007
MK-32	<0.0002	0.0006	<0.006	0.56	0.11	0.93	11.8	0.0014	<0.06	0.42	<0.0002	<0.0002	0.0002	<0.008	16.2	<0.007
MK-33	<0.0002	0.0005	<0.006	0.91	0.14	0.15	11.9	<0.0006	<0.06	0.41	<0.0002	<0.0002	<0.0001	<0.008	19.7	<0.007
MK-34	<0.0002	<0.0003	<0.006	0.19	0.64	0.14	7.4	<0.0006	<0.06	0.34	<0.0002	<0.0002	<0.0001	<0.008	20.4	<0.007
MK-35	<0.0002	0.0006	<0.006	0.24	0.11	0.55	6.7	0.0011	<0.06	0.28	0.0003	<0.0002	<0.0001	0.010	23.3	<0.007
MK-36	<0.0002	<0.0003	<0.006	0.51	0.46	0.12	12.9	<0.0006	<0.06	0.34	<0.0002	<0.0002	<0.0001	<0.008	21.4	<0.007
MK-37	0.0002	0.0007	<0.006	1.02	0.42	0.86	6.8	0.0015	<0.06	0.37	0.0002	<0.0002	<0.0001	<0.008	20.3	0.007
MK-38	<0.0002	<0.0003	<0.006	0.41	0.18	0.03	2.0	<0.0006	<0.06	0.22	<0.0002	<0.0002	<0.0001	<0.008	16.5	<0.007
MK-40	<0.0002	0.0005	<0.006	0.44	0.19	0.13	11.2	0.0006	0.47	0.35	<0.0002	<0.0002	<0.0001	<0.008	19.3	<0.007
MK-41	<0.0002	<0.0003	<0.006	0.45	NA	0.15	5.9	<0.0006	0.16	0.28	<0.0002	<0.0002	<0.0001	<0.008	18.2	<0.007
MK-42	<0.0002	<0.0003	<0.006	0.37	0.37	0.12	4.8	<0.0006	0.07	0.29	<0.0002	<0.0002	<0.0001	<0.008	16.3	<0.007
MK-43	<0.0002	<0.0003	0.006	0.33	0.80	0.03	18.9	<0.0006	2.57	0.41	<0.0002	<0.0002	<0.0001	<0.008	20.6	<0.007

Table A2.3 *(cont.)* Concentrations of elements in rice grains in the Mekong River Delta area in mg kg^{-1} (n = 78)

Sites	Hf	La	Li	Mo	Ni	Pb	Rb	Sb	Sn	Sr	Th	Tl	U	V	Zn	Zr
MK-44	<0.0002	<0.0003	<0.006	0.56	0.31	0.05	19.3	<0.0006	<0.06	0.36	<0.0002	<0.0002	<0.0001	<0.008	20.1	<0.007
MK-45	<0.0002	<0.0003	<0.006	0.22	0.26	0.09	13.5	<0.0006	0.98	0.33	<0.0002	<0.0002	<0.0001	<0.008	22.3	<0.007
MK-46	<0.0002	<0.0003	<0.006	0.13	0.18	0.06	15.3	<0.0006	0.27	0.44	<0.0002	<0.0002	<0.0001	<0.008	19.3	<0.007
MK-47	<0.0002	<0.0003	<0.006	0.33	0.63	0.04	15.8	<0.0006	0.40	0.30	<0.0002	<0.0002	<0.0001	<0.008	19.0	<0.007
MK-48	<0.0002	<0.0003	<0.006	0.52	NA	0.02	24.6	<0.0006	0.51	0.37	<0.0002	<0.0002	<0.0001	<0.008	20.6	<0.007
MK-49	<0.0002	0.0007	<0.006	0.21	0.40	0.88	9.6	0.0019	<0.06	0.26	<0.0002	<0.0002	<0.0001	<0.008	24.9	<0.007
MK-51	<0.0002	0.0003	<0.006	0.53	0.14	0.20	13.5	0.0010	0.08	0.43	<0.0002	<0.0002	<0.0001	<0.008	17.9	<0.007
MK-52	<0.0002	<0.0003	<0.006	0.17	0.61	0.20	2.8	<0.0006	<0.06	0.19	<0.0002	<0.0002	<0.0001	<0.008	19.3	<0.007
MK-53	<0.0002	<0.0003	<0.006	0.28	0.25	0.07	6.6	<0.0006	<0.06	0.28	<0.0002	<0.0002	<0.0001	<0.008	17.4	<0.007
MK-54	<0.0002	0.0005	<0.006	0.48	0.43	0.16	25.9	<0.0006	0.16	0.37	<0.0002	<0.0002	<0.0001	0.008	16.8	<0.007
MK-55	<0.0002	0.0005	<0.006	0.41	0.24	0.14	10.1	0.0010	0.16	0.31	0.0002	<0.0002	<0.0001	<0.008	19.0	<0.007
MK-56	<0.0002	<0.0003	<0.006	0.47	0.51	0.19	5.5	<0.0006	0.15	0.27	<0.0002	<0.0002	<0.0001	<0.008	16.5	<0.007
MK-57	<0.0002	0.0003	<0.006	0.40	0.21	0.20	6.6	0.0006	<0.06	0.40	<0.0002	<0.0002	<0.0001	<0.008	18.3	<0.007
MK-58	<0.0002	<0.0003	<0.006	0.33	0.27	0.12	8.7	<0.0006	0.13	0.42	<0.0002	<0.0002	<0.0001	<0.008	20.6	<0.007
MK-59	<0.0002	0.0003	<0.006	0.51	0.31	0.28	4.1	<0.0006	0.07	0.29	<0.0002	<0.0002	<0.0001	<0.008	18.1	<0.007
MK-60	<0.0002	<0.0003	<0.006	0.55	0.34	0.03	10.2	<0.0006	0.14	0.37	<0.0002	<0.0002	<0.0001	<0.008	23.7	<0.007
MK-61	<0.0002	<0.0003	<0.006	0.39	0.60	0.03	16.5	0.0006	0.32	0.42	<0.0002	<0.0002	<0.0001	0.016	19.9	<0.007
MK-62	<0.0002	<0.0003	<0.006	0.37	0.20	0.04	15.3	<0.0006	0.07	0.37	<0.0002	<0.0002	<0.0001	0.013	21.6	<0.007
MK-63	<0.0002	0.0003	<0.006	0.28	NA	0.42	11.4	0.0014	1.97	0.31	<0.0002	<0.0002	<0.0001	0.011	22.0	<0.007
MK-64	<0.0002	0.0004	0.028	0.13	NA	0.03	18.0	<0.0006	<0.06	0.21	<0.0002	<0.0002	<0.0001	0.008	26.6	<0.007
MK-65	<0.0002	0.0005	<0.006	0.11	0.26	0.06	15.4	<0.0006	<0.06	0.25	<0.0002	<0.0002	<0.0001	<0.008	17.3	<0.007
MK-66	<0.0002	0.0004	<0.006	0.12	0.30	0.51	18.1	0.0013	0.14	0.27	<0.0002	<0.0002	<0.0001	0.010	19.2	<0.007
MK-67	<0.0002	<0.0003	<0.006	0.42	0.40	0.03	1.1	<0.0006	0.07	0.32	<0.0002	<0.0002	<0.0001	<0.008	21.8	<0.007
MK-68	<0.0002	<0.0003	<0.006	0.42	0.36	0.06	1.5	<0.0006	0.07	0.35	<0.0002	<0.0002	<0.0001	<0.008	19.3	<0.007
MK-69	<0.0002	0.0005	<0.006	0.40	0.62	0.59	1.7	0.0013	0.07	0.47	<0.0002	<0.0002	<0.0001	0.016	19.6	<0.007
MK-70	<0.0002	0.0007	<0.006	0.28	0.11	0.05	5.2	<0.0006	<0.06	0.41	<0.0002	<0.0002	<0.0001	<0.008	17.6	<0.007
MK-71	<0.0002	0.0005	<0.006	0.35	0.13	0.30	5.6	<0.0006	<0.06	0.42	<0.0002	<0.0002	<0.0001	0.016	20.4	<0.007
MK-72	<0.0002	0.0003	0.008	0.82	0.28	0.08	2.0	0.0013	0.07	0.37	<0.0002	<0.0002	<0.0001	<0.008	21.1	<0.007
MK-73	<0.0002	<0.0003	0.010	0.60	0.35	0.02	3.9	<0.0006	<0.06	0.54	<0.0002	<0.0002	<0.0001	<0.008	22.4	<0.007
MK-74	<0.0002	0.0005	0.011	0.40	0.35	0.08	2.0	<0.0006	<0.06	0.48	<0.0002	<0.0002	<0.0001	<0.008	24.1	<0.007
MK-75	<0.0002	<0.0003	<0.006	0.52	0.20	0.07	6.7	<0.0006	<0.06	0.55	<0.0002	<0.0002	<0.0001	<0.008	24.4	<0.007
MK-76	<0.0002	<0.0003	<0.006	0.33	0.45	0.06	13.7	<0.0006	<0.06	0.38	<0.0002	<0.0002	<0.0001	0.009	15.8	<0.007
MK-77	<0.0002	<0.0003	<0.006	0.46	0.52	0.05	52.1	<0.0006	<0.06	0.47	<0.0002	<0.0002	<0.0001	0.008	18.5	<0.007
MK-78	<0.0002	0.0003	<0.006	0.53	0.38	0.06	12.0	<0.0006	<0.06	0.50	<0.0002	<0.0002	<0.0001	<0.008	19.3	<0.007
MK-79	<0.0002	0.0003	<0.006	0.56	0.96	0.04	28.0	<0.0006	<0.06	0.38	<0.0002	<0.0002	<0.0001	<0.008	17.9	<0.007
MK-80	<0.0002	<0.0003	<0.006	0.35	0.60	0.05	10.1	<0.0006	<0.06	0.42	<0.0002	<0.0002	<0.0001	<0.008	19.5	<0.007
MK-81	<0.0002	0.0003	0.007	0.31	0.38	0.09	14.3	<0.0006	0.12	0.24	0.0002	<0.0002	<0.0001	<0.008	18.4	<0.007
MK-82	<0.0002	<0.0003	0.006	0.18	NA	0.03	4.6	<0.0006	<0.06	0.20	<0.0002	<0.0002	<0.0001	0.012	20.7	<0.007

"<": lower than detection limit, NA: not analyzed

Table A2.4 Transfer factors of elements from soils into rice grains in the Mekong River Delta area (n = 78)

Sites	Al	Ca	Fe	K	Mg	Mn	Na	P	S	Ti	As	Ba	Bi	Cd	Ce	Co	Cr
MK-1	<0.00005	0.010	0.0002	0.10	0.16	0.02	0.001	4.0	1.1	<0.00001	0.007	0.0010	0.0007	0.008	<0.00001	0.0007	<0.001
MK-2	<0.00004	0.022	0.0003	0.11	0.20	0.09	0.002	7.4	2.2	<0.00001	0.012	0.0010	0.0013	0.191	0.00001	0.0008	<0.001
MK-3	<0.00005	0.020	0.0002	0.11	0.17	0.07	0.001	4.7	1.8	<0.00001	0.009	0.0017	0.0009	0.058	<0.00001	0.0009	<0.001
MK-4	<0.00006	0.016	0.0003	0.14	0.19	0.04	0.001	6.7	2.8	<0.00001	0.009	0.0015	0.0010	0.079	0.00001	0.0016	<0.001
MK-5	<0.00005	0.019	0.0002	0.12	0.17	0.03	0.001	5.2	2.6	<0.00001	0.008	0.0013	0.0009	0.059	<0.00001	0.0012	<0.001
MK-6	<0.00006	0.016	0.0002	0.15	0.19	0.03	0.001	5.7	5.3	0.00001	0.008	0.0016	0.0007	0.087	0.00002	0.0019	<0.001
MK-7	<0.00005	0.020	0.0003	0.14	0.23	0.06	0.002	6.4	2.1	0.00002	0.014	0.0016	0.0010	0.015	0.00001	0.0009	<0.001
MK-8	<0.00005	0.024	0.0003	0.14	0.20	0.02	0.002	4.3	3.9	0.00001	0.007	0.0036	0.0040	0.101	0.00001	0.0016	<0.001
MK-9	<0.00004	0.019	0.0002	0.10	0.15	0.06	0.001	3.5	1.7	0.00002	0.009	0.0006	<0.0005	0.024	<0.00001	0.0009	<0.001
MK-10	<0.00004	0.022	0.0002	0.10	0.14	0.07	0.001	3.4	0.8	0.00003	0.027	0.0005	0.0005	0.010	0.00001	0.0008	<0.001
MK-11	<0.00006	0.023	0.0002	0.14	0.19	0.07	0.001	2.4	1.5	0.00009	0.033	0.0008	0.0019	0.181	<0.00001	0.0016	<0.002
MK-12	<0.00005	0.019	0.0002	0.11	0.15	0.03	0.001	4.7	2.4	<0.00001	0.026	0.0010	0.0006	0.010	<0.00001	0.0015	<0.001
MK-13	<0.00005	0.029	0.0002	0.12	0.17	0.06	0.001	3.5	1.8	<0.00001	0.019	0.0007	0.0010	0.025	<0.00001	0.0014	<0.001
MK-14	<0.00006	0.025	0.0003	0.13	0.20	0.09	0.001	5.4	1.5	<0.00001	0.034	0.0010	<0.0006	0.023	<0.00001	0.0015	<0.001
MK-15	<0.00006	0.020	0.0002	0.12	0.15	0.04	0.001	3.6	1.6	<0.00001	0.020	0.0009	0.0013	0.072	<0.00001	0.0016	<0.001
MK-16	<0.00006	0.018	0.0002	0.12	0.14	0.03	0.001	3.2	2.4	<0.00001	0.013	0.0019	0.0009	0.084	<0.00001	0.0014	<0.002
MK-17	<0.00006	0.023	0.0002	0.14	0.19	0.05	0.001	2.6	2.3	<0.00001	0.013	0.0010	0.0010	0.199	<0.00001	0.0015	<0.002
MK-18	<0.00004	0.027	0.0002	0.11	0.16	0.08	0.001	3.1	1.2	<0.00001	0.015	0.0006	0.0005	0.105	<0.00001	0.0011	<0.001
MK-19	<0.00006	0.026	0.0002	0.13	0.16	0.03	0.001	2.1	2.7	<0.00001	0.044	0.0007	<0.0005	0.006	<0.00001	0.0021	<0.002
MK-20	<0.00005	0.028	0.0003	0.13	0.17	0.05	0.001	3.2	2.0	<0.00001	0.022	0.0014	0.0011	0.027	<0.00001	0.0009	<0.001
MK-21	<0.00005	0.031	0.0003	0.16	0.21	0.12	0.001	3.8	1.5	<0.00001	0.018	0.0015	0.0037	0.227	0.00002	0.0020	<0.001
MK-22	<0.00004	0.029	0.0003	0.17	0.21	0.14	0.002	3.9	1.4	<0.00001	0.011	0.0025	<0.0005	0.268	<0.00001	0.0012	<0.001
MK-23	<0.00004	0.018	0.0004	0.16	0.21	0.08	0.001	4.8	0.6	<0.00001	0.012	0.0022	0.0008	0.114	<0.00001	0.0006	<0.001
MK-24	<0.00004	0.024	0.0003	0.15	0.26	0.10	0.001	5.0	1.4	<0.00001	0.014	0.0018	0.0014	0.149	<0.00001	0.0012	<0.001
MK-25	<0.00005	0.030	0.0004	0.16	0.21	0.17	0.001	5.4	1.5	0.00002	0.016	0.0018	0.0010	0.727	<0.00001	0.0032	<0.002
MK-26	<0.00004	0.027	0.0002	0.11	0.18	0.05	0.002	3.7	1.1	<0.00001	0.014	0.0013	0.0022	0.067	<0.00001	0.0012	<0.001
MK-27	<0.00005	0.028	0.0003	0.13	0.21	0.07	0.001	8.6	1.4	<0.00001	0.015	0.0023	0.0036	0.110	<0.00001	0.0019	<0.001
MK-30	<0.00004	0.037	0.0003	0.14	0.20	0.12	0.001	6.8	1.8	<0.00001	0.019	0.0036	0.0012	0.021	<0.00001	0.0008	<0.001
MK-31	<0.00005	0.022	0.0002	0.11	0.17	0.06	0.001	2.9	1.8	<0.00001	0.019	0.0016	0.0009	0.039	<0.00001	0.0014	<0.001
MK-32	<0.00004	0.028	0.0003	0.12	0.18	0.08	0.001	4.5	1.7	0.00002	0.022	0.0022	0.0022	0.013	0.00001	0.0017	<0.001
MK-33	<0.00004	0.032	0.0003	0.12	0.19	0.09	0.001	3.8	1.4	<0.00001	0.023	0.0015	0.0006	0.050	0.00001	0.0016	<0.001
MK-34	<0.00005	0.025	0.0003	0.11	0.16	0.10	0.001	3.4	1.7	<0.00001	0.010	0.0018	<0.0005	0.448	<0.00001	0.0019	<0.001
MK-35	<0.00004	0.022	0.0003	0.12	0.19	0.07	0.005	2.8	0.8	0.00002	0.015	0.0007	0.0048	0.059	0.00001	0.0012	<0.001
MK-36	<0.00004	0.028	0.0003	0.12	0.20	0.14	0.002	3.0	1.2	<0.00001	0.006	0.0006	<0.0005	0.256	<0.00001	0.0021	<0.001
MK-37	<0.00005	0.032	0.0003	0.14	0.21	0.09	0.001	4.3	2.7	0.00001	0.012	0.0031	0.0032	0.304	0.00002	0.0028	<0.001
MK-38	<0.00004	0.019	0.0002	0.10	0.16	0.06	0.001	3.2	1.6	<0.00001	0.016	0.0008	0.0007	0.085	<0.00001	0.0009	<0.001
MK-40	<0.00004	0.022	0.0003	0.12	0.17	0.10	0.001	3.0	1.0	0.00003	0.023	0.0011	0.0013	0.196	0.00001	0.0015	0.002
MK-41	<0.00004	0.026	0.0003	0.12	0.19	0.09	0.002	4.4	0.9	0.00003	0.016	0.0009	0.0014	0.051	<0.00001	0.0022	NA
MK-42	<0.00005	0.019	0.0003	0.12	0.18	0.09	0.001	3.7	0.6	<0.00001	0.012	0.0009	0.0009	0.115	<0.00001	0.0019	0.003
MK-43	<0.00006	0.030	0.0005	0.16	0.27	0.19	0.001	6.6	1.1	<0.00001	0.014	0.0016	0.0014	0.321	<0.00001	0.0062	0.011

Table A2.4 (*cont.*) Transfer factors of elements from soils into rice grains in the Mekong River Delta area (n = 78)

Sites	Al	Ca	Fe	K	Mg	Mn	Na	P	S	Ti	As	Ba	Bi	Cd	Ce	Co	Cr
MK-44	<0.00004	0.031	0.0004	0.11	0.19	0.16	0.002	6.4	0.8	<0.00001	0.015	0.0012	<0.0005	0.187	<0.00001	0.0024	0.003
MK-45	<0.00005	0.028	0.0004	0.16	0.26	0.13	0.002	6.1	0.7	<0.00001	0.018	0.0006	<0.0005	0.115	<0.00001	0.0011	0.006
MK-47	<0.00005	0.023	0.0005	0.13	0.22	0.08	0.001	4.8	0.4	<0.00001	0.013	0.0008	0.0006	0.047	<0.00001	0.0016	NA
MK-48	0.00006	0.033	0.0009	0.13	0.28	0.21	0.002	6.7	0.7	<0.00001	0.018	0.0006	0.0013	0.314	<0.00001	0.0082	NA
MK-49	<0.00004	0.036	0.0005	0.12	0.27	0.21	0.002	4.9	0.6	0.00003	0.015	0.0007	0.0023	0.232	0.00002	0.0030	<0.001
MK-51	<0.00006	0.035	0.0003	0.16	0.26	0.08	0.002	5.0	2.2	0.00007	0.037	0.0021	0.0012	0.011	0.00001	0.0019	0.003
MK-52	<0.00005	0.017	0.0003	0.14	0.20	0.03	0.002	3.9	0.3	0.00001	0.009	0.0002	0.0007	0.047	<0.00001	0.0038	<0.001
MK-53	<0.00004	0.024	0.0002	0.12	0.18	0.09	0.002	4.6	0.5	<0.00001	0.018	0.0003	0.0005	0.146	<0.00001	0.0018	<0.001
MK-54	<0.00004	0.028	0.0003	0.13	0.19	0.12	0.002	5.4	1.0	<0.00001	0.016	0.0019	0.0006	0.125	0.00001	0.0022	0.004
MK-55	0.00019	0.024	0.0003	0.13	0.19	0.08	0.002	5.1	1.0	<0.00001	0.019	0.0018	0.0009	0.011	0.00001	0.0017	0.002
MK-56	<0.00004	0.018	0.0004	0.11	0.16	0.07	0.002	3.3	0.9	<0.00001	0.010	0.0010	0.0005	0.136	<0.00001	0.0014	0.007
MK-57	<0.00005	0.024	0.0003	0.13	0.22	0.05	0.003	6.0	2.1	0.00002	0.013	0.0026	0.0009	0.071	0.00001	0.0011	<0.001
MK-58	<0.00005	0.026	0.0003	0.14	0.23	0.09	0.002	6.5	1.7	<0.00001	0.010	0.0034	0.0011	0.050	<0.00001	0.0012	<0.001
MK-59	<0.00005	0.011	0.0003	0.12	0.19	0.04	0.001	3.1	1.2	0.00002	0.011	0.0004	0.0009	0.043	<0.00001	0.0015	<0.001
MK-60	<0.00005	0.024	0.0003	0.14	0.20	0.05	0.001	4.0	1.7	<0.00001	0.015	0.0017	0.0020	0.193	<0.00001	0.0014	0.007
MK-61	<0.00005	0.028	0.0003	0.16	0.19	0.06	0.001	4.2	2.7	<0.00001	0.010	0.0026	<0.0005	0.368	<0.00001	0.0020	0.004
MK-62	0.00007	0.027	0.0004	0.17	0.23	0.08	0.001	3.7	2.1	<0.00001	0.012	0.0022	0.0010	0.195	<0.00001	0.0010	0.004
MK-63	<0.00005	0.022	NA	0.14	0.20	0.04	0.001	3.0	2.1	<0.00001	0.017	0.0009	0.0015	0.115	0.00001	0.0041	NA
MK-64	<0.00004	0.045	0.0003	0.13	0.23	0.20	0.001	7.4	0.7	<0.00001	0.006	0.0002	<0.0005	0.432	0.00001	0.0107	0.001
MK-65	<0.00004	0.027	0.0003	0.12	0.19	0.07	0.002	6.0	0.3	<0.00001	0.011	0.0011	<0.0005	0.008	0.00001	0.0006	0.003
MK-66	<0.00004	0.022	0.0003	0.13	0.19	0.06	0.002	7.9	0.2	0.00001	0.015	0.0015	0.0013	0.005	0.00001	0.0008	0.004
MK-67	<0.00004	0.026	0.0004	0.12	0.19	0.16	0.003	4.2	1.2	<0.00001	0.011	0.0007	<0.0005	0.927	<0.00001	0.0028	0.002
MK-68	<0.00004	0.026	0.0004	0.13	0.19	0.15	0.003	3.8	1.0	<0.00001	0.015	0.0012	<0.0005	0.897	<0.00001	0.0029	0.002
MK-69	<0.00004	0.025	0.0004	0.12	0.19	0.13	0.004	3.4	0.9	<0.00001	0.009	0.0014	0.0010	0.598	0.00001	0.0015	0.001
MK-70	<0.00004	0.022	0.0003	0.14	0.19	0.07	0.006	4.0	1.0	<0.00001	0.007	0.0008	<0.0005	0.161	0.00002	0.0009	<0.001
MK-71	<0.00004	0.016	0.0003	0.16	0.22	0.09	0.006	3.7	0.8	0.00001	0.007	0.0011	<0.0005	0.190	0.00001	0.0011	<0.001
MK-72	<0.00006	0.017	0.0003	0.16	0.27	0.10	0.002	2.6	0.9	<0.00001	0.008	0.0003	<0.0005	0.115	0.00001	0.0021	<0.001
MK-73	<0.00005	0.022	0.0003	0.15	0.23	0.10	0.002	3.6	0.8	<0.00001	0.006	0.0004	<0.0005	0.148	<0.00001	0.0025	<0.001
MK-74	<0.00006	0.013	0.0003	0.16	0.28	0.16	0.003	2.9	0.7	0.00005	0.010	0.0004	0.0014	0.082	0.00001	0.0030	<0.001
MK-75	<0.00006	0.036	0.0005	0.16	0.34	0.07	0.001	6.5	1.0	<0.00001	0.013	0.0009	0.0011	0.070	<0.00001	0.0028	<0.001
MK-76	<0.00004	0.024	0.0003	0.13	0.24	0.12	0.002	4.0	0.6	<0.00001	0.013	0.0010	<0.0004	0.038	<0.00001	0.0018	<0.001
MK-77	<0.00005	0.023	0.0003	0.14	0.24	0.08	0.001	5.2	0.9	<0.00001	0.036	0.0006	<0.0005	0.064	<0.00001	0.0022	<0.001
MK-78	<0.00004	0.025	0.0003	0.14	0.22	0.08	0.002	4.7	1.3	<0.00001	0.014	0.0027	0.0008	0.072	<0.00001	0.0030	<0.001
MK-79	<0.00004	0.026	0.0003	0.12	0.19	0.13	0.004	4.2	0.6	0.00001	0.007	0.0009	<0.0004	0.118	<0.00001	0.0032	<0.001
MK-80	<0.00004	0.024	0.0003	0.13	0.21	0.17	0.002	5.1	0.7	<0.00001	0.008	0.0012	<0.0005	0.318	<0.00001	0.0032	<0.001
MK-81	<0.00004	0.022	0.0003	0.14	0.24	0.08	0.001	4.7	0.4	0.00002	0.009	0.0005	<0.0005	0.043	0.00001	0.0015	<0.001
MK-82	0.00007	0.027	0.0005	0.18	0.32	0.13	0.001	2.6	0.2	<0.00001	0.010	0.0001	<0.0006	0.115	<0.00001	0.0086	<0.001

Table A2.4 *(cont.)* Transfer factors of elements from soils into rice grains in the Mekong River Delta area (n = 78)

Sites	Cs	Cu	Hf	La	Li	Mo	Ni	Pb	Rb	Sb	Sn	Sr	Th	Tl	U	V	Zn	Zr
MK-1	0.0031	0.09	<0.00005	<0.00001	<0.0001	0.52	0.002	0.0062	0.13	0.0004	<0.015	0.003	<0.00001	<0.0003	<0.00003	<0.0001	0.17	<0.00005
MK-2	0.0032	0.07	<0.00005	0.00001	<0.0001	1.20	0.003	0.0105	0.15	0.0011	<0.013	0.003	<0.00001	<0.0002	<0.00002	<0.0001	0.20	<0.00005
MK-3	0.0021	0.09	<0.00004	<0.00001	<0.0001	0.49	0.006	0.0040	0.10	<0.0002	0.016	0.004	<0.00001	<0.0003	<0.00002	<0.0001	0.17	<0.00004
MK-4	0.0037	0.19	<0.00004	0.00001	<0.0002	0.78	0.011	0.0154	0.15	0.0003	<0.016	0.003	<0.00001	<0.0004	<0.00003	0.0003	0.29	<0.00004
MK-5	0.0022	0.10	<0.00004	<0.00001	<0.0001	0.39	0.005	0.0052	0.10	<0.0003	<0.014	0.003	<0.00001	<0.0003	<0.00002	<0.0001	0.15	<0.00004
MK-6	0.0027	0.40	<0.00004	0.00003	<0.0002	0.53	0.008	0.0205	0.14	0.0003	<0.017	0.003	<0.00001	<0.0004	<0.00003	0.0001	0.27	0.00004
MK-7	0.0016	0.10	<0.00004	0.00001	<0.0001	0.91	0.002	0.0066	0.09	<0.0003	<0.016	0.003	0.00001	<0.0003	<0.00002	0.0002	0.18	<0.00004
MK-8	0.0014	0.16	<0.00004	0.00001	0.0001	0.43	0.011	0.0095	0.06	<0.0003	<0.015	0.004	<0.00001	<0.0003	<0.00002	<0.0001	0.24	<0.00004
MK-9	0.0003	0.12	0.00017	<0.00001	<0.0001	0.62	0.003	0.0037	0.02	<0.0003	<0.013	0.002	<0.00001	<0.0003	<0.00002	0.0001	0.15	0.00018
MK-10	0.0009	0.03	<0.00005	0.00001	<0.0001	0.37	0.001	0.0072	0.04	<0.0002	<0.012	0.003	<0.00001	<0.0002	<0.00002	0.0001	0.18	<0.00005
MK-11	0.0027	0.11	<0.00004	<0.00001	<0.0002	0.90	0.011	0.0041	0.10	<0.0003	<0.017	0.003	<0.00002	<0.0004	<0.00003	<0.0001	0.25	<0.00004
MK-12	0.0030	0.07	<0.00005	<0.00001	<0.0001	0.59	0.002	0.0084	0.11	<0.0003	0.018	0.003	<0.00001	<0.0003	<0.00003	<0.0001	0.20	<0.00004
MK-13	0.0036	0.04	<0.00004	<0.00001	<0.0001	0.58	0.002	0.0105	0.15	0.0005	<0.013	0.004	<0.00001	<0.0003	<0.00002	<0.0001	0.23	<0.00004
MK-14	0.0008	0.06	<0.00004	<0.00001	<0.0002	0.79	0.004	0.0006	0.05	<0.0001	0.019	0.004	<0.00001	<0.0004	<0.00002	<0.0001	0.23	<0.00004
MK-15	0.0021	0.10	<0.00004	<0.00001	<0.0002	0.59	0.005	0.0052	0.06	<0.0003	<0.017	0.003	<0.00001	<0.0004	<0.00002	<0.0001	0.24	<0.00004
MK-16	0.0055	0.10	<0.00005	<0.00001	<0.0002	0.61	0.008	0.0013	0.14	<0.0003	<0.017	0.004	<0.00001	<0.0004	<0.00002	<0.0001	0.21	<0.00005
MK-17	0.0050	0.22	<0.00005	<0.00001	<0.0002	0.43	0.019	0.0065	0.17	<0.0003	<0.016	0.004	<0.00001	<0.0004	<0.00002	0.0002	0.28	<0.00005
MK-18	0.0014	0.07	<0.00005	<0.00001	<0.0001	0.48	0.005	0.0018	0.04	<0.0002	<0.013	0.003	<0.00001	<0.0003	<0.00002	<0.0001	0.20	<0.00005
MK-19	0.0064	0.08	<0.00005	<0.00001	0.0002	1.05	0.002	0.0015	0.18	<0.0002	<0.015	0.005	<0.00001	<0.0003	<0.00002	<0.0001	0.21	<0.00005
MK-20	0.0006	0.06	<0.00005	0.00001	<0.0001	0.18	0.003	0.0104	0.04	<0.0003	0.017	0.005	<0.00001	<0.0003	<0.00002	<0.0001	0.21	<0.00005
MK-21	0.0040	0.07	<0.00005	0.00002	<0.0001	0.55	0.006	0.0118	0.15	0.0008	<0.015	0.006	<0.00001	<0.0003	<0.00002	<0.0001	0.25	<0.00005
MK-22	0.0024	0.11	<0.00005	<0.00001	<0.0001	0.61	0.006	0.0026	0.14	<0.0003	<0.014	0.007	<0.00001	<0.0003	<0.00002	<0.0001	0.23	<0.00005
MK-23	0.0034	0.08	<0.00006	<0.00001	<0.0001	0.44	0.003	0.0030	0.17	<0.0003	0.016	0.006	<0.00001	<0.0003	<0.00002	<0.0001	0.19	<0.00005
MK-24	0.0046	0.10	<0.00005	<0.00001	<0.0001	0.51	0.009	0.0013	0.15	<0.0003	<0.014	0.005	<0.00001	<0.0003	<0.00002	<0.0001	0.21	<0.00005
MK-25	0.0037	0.14	<0.00005	<0.00001	<0.0001	0.61	0.014	0.0033	0.11	0.0003	<0.015	0.006	<0.00001	<0.0003	<0.00002	<0.0001	0.25	<0.00005
MK-26	0.0011	0.07	<0.00006	<0.00001	<0.0001	0.35	0.004	0.0017	0.06	<0.0005	<0.013	0.006	<0.00001	<0.0003	<0.00002	<0.0001	0.18	<0.00005
MK-27	0.0008	0.13	<0.00004	<0.00001	0.0001	0.33	0.009	0.0014	0.05	<0.0006	<0.015	0.006	<0.00001	<0.0003	<0.00002	0.0001	0.27	<0.00004
MK-30	0.0034	0.12	<0.00005	<0.00001	<0.0001	0.39	0.007	0.0036	0.12	<0.0003	0.022	0.004	<0.00001	<0.0003	<0.00002	<0.0001	0.21	<0.00005
MK-31	0.0008	0.10	<0.00005	<0.00001	<0.0001	0.64	0.004	0.0013	0.05	<0.0003	<0.014	0.004	<0.00001	<0.0003	<0.00002	<0.0001	0.19	<0.00005
MK-32	0.0019	0.08	<0.00005	0.00001	<0.0001	0.90	0.003	0.0320	0.09	0.0005	<0.014	0.005	<0.00001	<0.0003	0.00004	<0.0001	0.17	<0.00005
MK-33	0.0018	0.06	<0.00005	0.00001	<0.0001	1.25	0.004	0.0054	0.09	<0.0003	<0.013	0.005	<0.00001	<0.0003	<0.00002	<0.0001	0.19	<0.00005
MK-34	0.0018	0.13	<0.00005	<0.00001	<0.0001	0.25	0.018	0.0056	0.06	<0.0003	<0.015	0.004	<0.00001	<0.0003	<0.00002	<0.0001	0.23	<0.00005
MK-35	0.0022	0.09	<0.00005	0.00001	<0.0001	0.39	0.003	0.0204	0.05	0.0006	<0.013	0.003	0.00002	<0.0003	<0.00002	0.0001	0.25	<0.00004
MK-36	0.0031	0.17	<0.00005	<0.00001	<0.0001	0.47	0.010	0.0042	0.10	<0.0003	<0.014	0.004	<0.00001	<0.0003	<0.00002	<0.0001	0.18	<0.00005
MK-37	0.0013	0.12	0.00004	0.00002	<0.0001	1.62	0.012	0.0339	0.06	0.0008	<0.016	0.005	0.00001	<0.0003	<0.00002	<0.0001	0.23	0.00005
MK-38	0.0004	0.09	<0.00005	<0.00001	<0.0001	0.49	0.005	0.0013	0.02	<0.0003	<0.013	0.003	<0.00001	<0.0003	<0.00002	<0.0001	0.18	<0.00005
MK-40	0.0022	0.07	<0.00005	0.00001	<0.0001	0.52	0.005	0.0046	0.08	0.0003	0.113	0.004	<0.00001	<0.0003	<0.00002	<0.0001	0.19	<0.00005
MK-41	0.0010	0.05	<0.00005	<0.00001	<0.0001	0.54	NA	0.0050	0.04	<0.0002	0.035	0.003	<0.00001	<0.0003	<0.00002	<0.0001	0.17	<0.00005
MK-42	0.0011	0.11	<0.00005	<0.00001	<0.0001	0.41	0.010	0.0044	0.04	<0.0002	0.016	0.004	<0.00001	<0.0003	<0.00002	<0.0001	0.17	<0.00005
MK-43	0.0066	0.13	<0.00005	<0.00001	0.0001	0.35	0.031	0.0015	0.19	<0.0004	0.762	0.005	<0.00001	<0.0004	<0.00003	<0.0001	0.33	<0.00004

Table A2.4 *(cont.)* Transfer factors of elements from soils into rice grains in the Mekong River Delta area (n = 78)

Sites	Cs	Cu	Hf	La	Li	Mo	Ni	Pb	Rb	Sb	Sn	Sr	Th	Tl	U	V	Zn	Zr
MK-44	0.0056	0.10	<0.00005	<0.00001	<0.0001	0.55	0.010	0.0019	0.15	<0.0004	<0.014	0.004	<0.00001	<0.0003	<0.00002	<0.0001	0.27	<0.00005
MK-45	0.0029	0.11	<0.00005	<0.00001	<0.0001	0.27	0.008	0.0035	0.12	<0.0003	0.237	0.004	<0.00001	<0.0003	<0.00002	<0.0001	0.28	<0.00004
MK-46	0.0036	0.08	<0.00005	<0.00001	<0.0001	0.10	0.007	0.0028	0.13	<0.0004	0.068	0.005	<0.00001	<0.0003	<0.00002	<0.0001	0.36	<0.00004
MK-47	0.0036	0.05	<0.00005	<0.00001	<0.0001	0.31	0.020	0.0016	0.13	<0.0004	0.100	0.003	<0.00001	<0.0003	<0.00002	<0.0001	0.26	<0.00005
MK-48	0.0113	0.14	<0.00005	<0.00001	<0.0001	0.34	NA	0.0010	0.21	<0.0004	0.129	0.005	<0.00001	<0.0003	<0.00002	<0.0001	0.40	<0.00005
MK-49	0.0025	0.14	<0.00005	0.00002	<0.0001	0.18	0.013	0.0332	0.07	0.0012	<0.014	0.003	<0.00001	<0.0003	<0.00002	<0.0001	0.36	<0.00005
MK-51	0.0046	0.06	<0.00005	0.00001	<0.0002	0.88	0.005	0.0089	0.14	0.0005	0.024	0.006	<0.00002	<0.0004	<0.00003	<0.0001	0.25	<0.00005
MK-52	0.0003	0.08	<0.00005	<0.00001	<0.0001	0.16	0.014	0.0072	0.02	<0.0003	<0.014	0.002	<0.00001	<0.0003	<0.00002	<0.0001	0.18	<0.00005
MK-53	0.0010	0.11	<0.00005	<0.00001	<0.0001	0.25	0.006	0.0025	0.05	<0.0003	<0.014	0.003	<0.00001	<0.0003	<0.00002	<0.0001	0.18	<0.00005
MK-54	0.0045	0.10	<0.00005	0.00001	<0.0001	0.52	0.011	0.0054	0.19	<0.0003	0.037	0.005	<0.00001	<0.0003	<0.00002	0.0001	0.16	<0.00005
MK-55	0.0014	0.18	<0.00006	0.00001	<0.0001	0.36	0.005	0.0044	0.07	0.0004	0.036	0.004	0.00001	<0.0003	<0.00002	<0.0001	0.17	<0.00005
MK-56	0.0009	0.08	<0.00006	<0.00001	<0.0001	0.42	0.010	0.0059	0.04	<0.0002	0.031	0.003	<0.00001	<0.0003	<0.00002	<0.0001	0.14	<0.00005
MK-57	0.0009	0.10	<0.00005	0.00001	<0.0001	0.43	0.005	0.0076	0.05	0.0003	<0.016	0.005	<0.00001	<0.0003	<0.00002	<0.0001	0.17	<0.00005
MK-58	0.0011	0.11	<0.00005	<0.00001	<0.0001	0.34	0.007	0.0045	0.07	<0.0003	0.033	0.005	<0.00001	<0.0003	<0.00002	<0.0001	0.20	<0.00005
MK-59	0.0010	0.13	<0.00006	0.00001	<0.0001	0.75	0.009	0.0120	0.04	<0.0003	0.021	0.003	<0.00002	<0.0003	<0.00003	<0.0001	0.21	<0.00006
MK-60	0.0018	0.09	<0.00006	<0.00001	<0.0001	0.83	0.009	0.0011	0.08	<0.0003	0.033	0.005	<0.00001	<0.0003	<0.00003	<0.0001	0.25	<0.00005
MK-61	0.0038	0.13	<0.00005	<0.00001	<0.0002	0.61	0.019	0.0014	0.15	0.0003	0.084	0.005	<0.00001	<0.0004	<0.00002	0.0002	0.24	<0.00005
MK-62	0.0029	0.10	<0.00004	<0.00001	<0.0001	0.58	0.006	0.0017	0.14	<0.0003	0.020	0.005	<0.00001	<0.0003	<0.00002	0.0001	0.25	<0.00004
MK-63	0.0045	0.11	<0.00005	0.00001	<0.0001	0.41	NA	0.0158	0.10	0.0007	0.491	0.004	<0.00001	<0.0003	<0.00002	0.0001	0.24	<0.00004
MK-64	0.0039	0.17	<0.00004	0.00001	0.0005	0.13	NA	0.0010	0.14	<0.0003	<0.013	0.003	<0.00001	<0.0003	<0.00002	0.0001	0.30	<0.00004
MK-65	0.0032	0.05	<0.00005	0.00001	<0.0001	0.12	0.006	0.0021	0.11	<0.0003	<0.014	0.003	<0.00001	<0.0003	<0.00002	<0.0001	0.13	<0.00005
MK-66	0.0035	0.04	<0.00005	0.00001	<0.0001	0.14	0.007	0.0177	0.13	0.0007	0.032	0.003	<0.00001	<0.0003	<0.00002	0.0001	0.16	<0.00004
MK-67	0.0001	0.20	<0.00005	<0.00001	<0.0001	0.44	0.012	0.0011	0.01	<0.0004	0.017	0.004	<0.00001	<0.0003	<0.00002	<0.0001	0.28	<0.00004
MK-68	0.0002	0.16	<0.00005	<0.00001	<0.0001	0.41	0.011	0.0023	0.01	<0.0004	0.017	0.004	<0.00001	<0.0003	<0.00002	<0.0001	0.24	<0.00004
MK-69	0.0002	0.21	<0.00005	0.00001	<0.0001	0.43	0.019	0.0230	0.01	0.0009	0.015	0.005	<0.00001	<0.0003	<0.00002	0.0001	0.25	<0.00004
MK-70	0.0007	0.08	<0.00005	0.00002	<0.0001	0.30	0.003	0.0019	0.03	<0.0004	<0.013	0.005	<0.00001	<0.0003	<0.00002	<0.0001	0.22	<0.00004
MK-71	0.0008	0.09	<0.00005	0.00001	<0.0001	0.38	0.004	0.0109	0.04	<0.0003	<0.013	0.005	<0.00001	<0.0003	<0.00002	0.0001	0.26	<0.00005
MK-72	0.0002	0.15	<0.00004	0.00001	0.0002	0.49	0.010	0.0031	0.02	0.0010	0.017	0.004	<0.00001	<0.0004	<0.00002	<0.0001	0.29	<0.00004
MK-73	0.0005	0.17	<0.00004	<0.00001	0.0002	0.41	0.012	0.0008	0.03	<0.0005	<0.016	0.005	<0.00001	<0.0004	<0.00003	<0.0001	0.31	<0.00004
MK-74	0.0003	0.17	<0.00004	0.00001	0.0003	0.27	0.014	0.0034	0.02	<0.0005	<0.016	0.004	<0.00001	<0.0004	<0.00002	<0.0001	0.35	<0.00004
MK-75	0.0013	0.13	<0.00004	<0.00001	<0.0001	0.71	0.008	0.0027	0.06	<0.0004	<0.014	0.007	<0.00001	<0.0004	<0.00002	<0.0001	0.37	<0.00004
MK-76	0.0025	0.10	<0.00005	<0.00001	<0.0001	0.19	0.012	0.0020	0.11	<0.0003	<0.014	0.005	<0.00001	<0.0003	<0.00002	0.0001	0.19	<0.00004
MK-77	0.0064	0.07	<0.00005	<0.00001	<0.0001	0.51	0.014	0.0018	0.45	<0.0003	<0.015	0.006	<0.00001	<0.0003	<0.00002	0.0001	0.16	<0.00005
MK-78	0.0024	0.13	<0.00005	0.00001	<0.0001	0.45	0.010	0.0020	0.10	<0.0003	<0.014	0.006	<0.00001	<0.0003	<0.00002	<0.0001	0.19	<0.00005
MK-79	0.0099	0.08	<0.00005	0.00001	<0.0001	0.21	0.019	0.0011	0.21	<0.0002	<0.014	0.005	<0.00001	<0.0003	<0.00002	<0.0001	0.16	<0.00005
MK-80	0.0034	0.15	<0.00005	<0.00001	<0.0001	0.28	0.017	0.0018	0.08	<0.0003	<0.014	0.006	<0.00001	<0.0003	<0.00002	<0.0001	0.23	<0.00005
MK-81	0.0032	0.06	<0.00005	0.00001	0.0001	0.21	0.009	0.0032	0.12	<0.0003	0.031	0.003	0.00001	<0.0003	<0.00002	<0.0001	0.18	<0.00005
MK-82	0.0011	0.16	<0.00005	<0.00001	0.0001	0.13	NA	0.0011	0.04	<0.0004	<0.015	0.002	<0.00001	<0.0003	<0.00002	0.0001	0.30	<0.00004

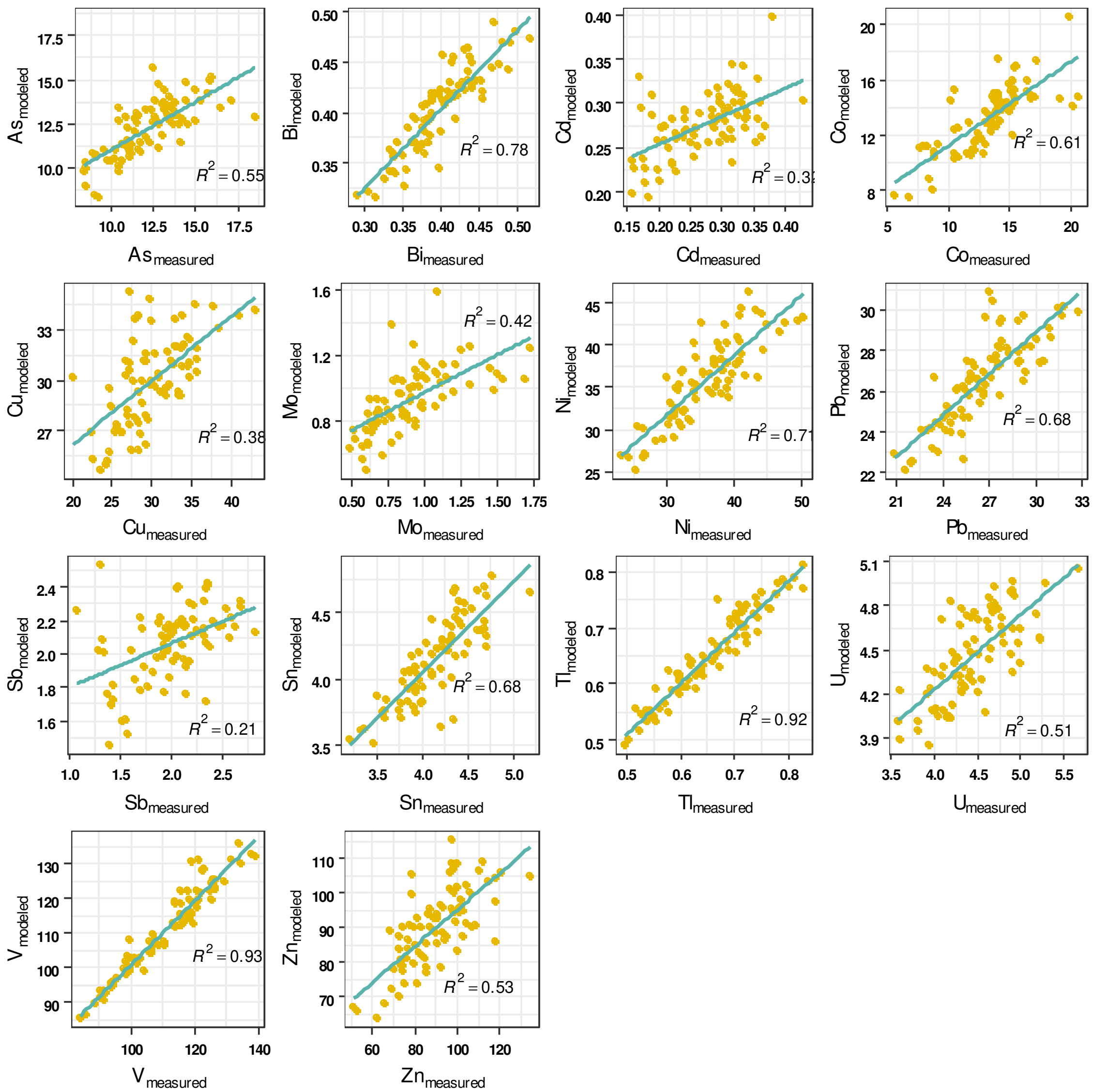


Fig. A2.1 Scattergram of measured contents versus modeled contents of selected trace elements in soils in the Mekong River (in mg kg^{-1}). The modeled values are obtained by using regression models based on soil parameters according to Table 4.2 in the main text.

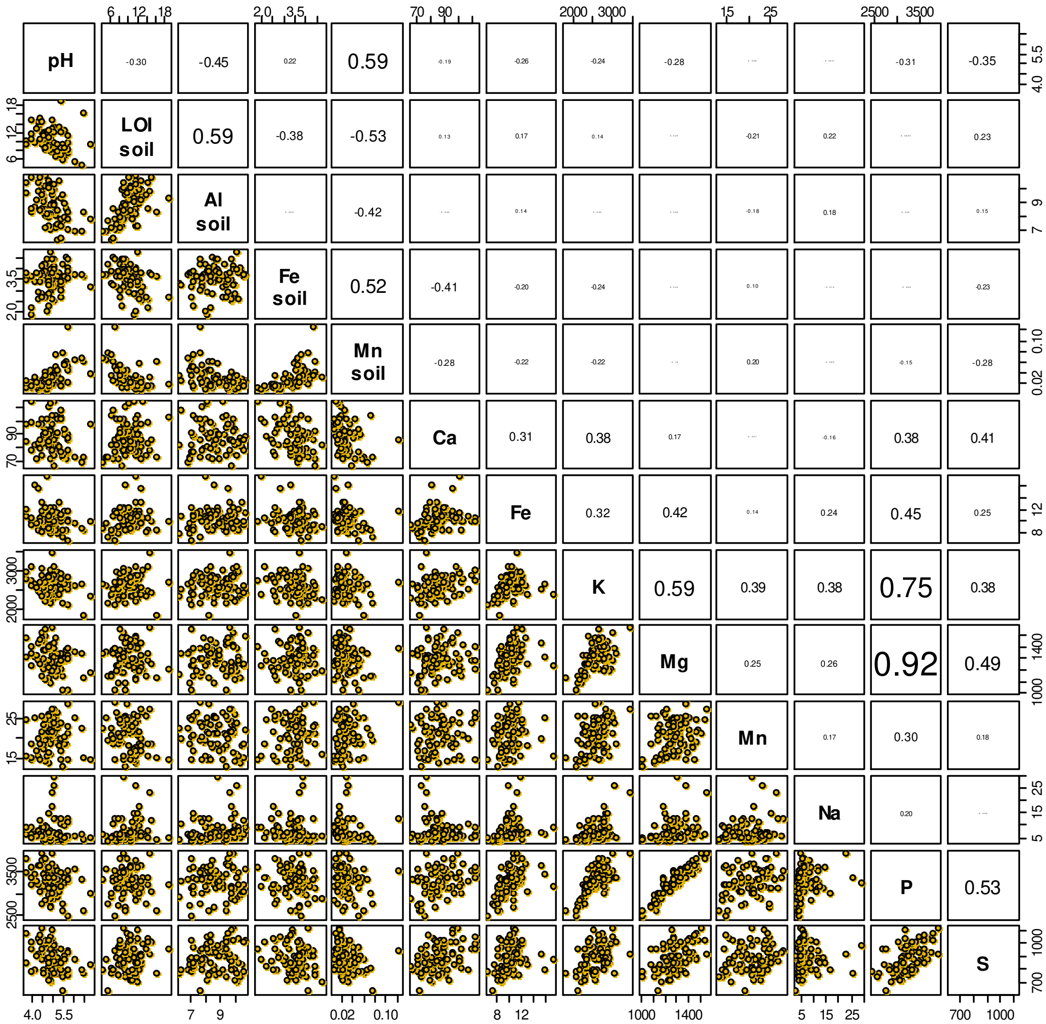


Fig. A2.2 Scattergram and correlation matrix for nutrient concentrations in rice grains in the Mekong River Delta area including relations between grain concentrations and soil parameters (soil concentrations in wt. %, grain concentrations in mg kg^{-1})

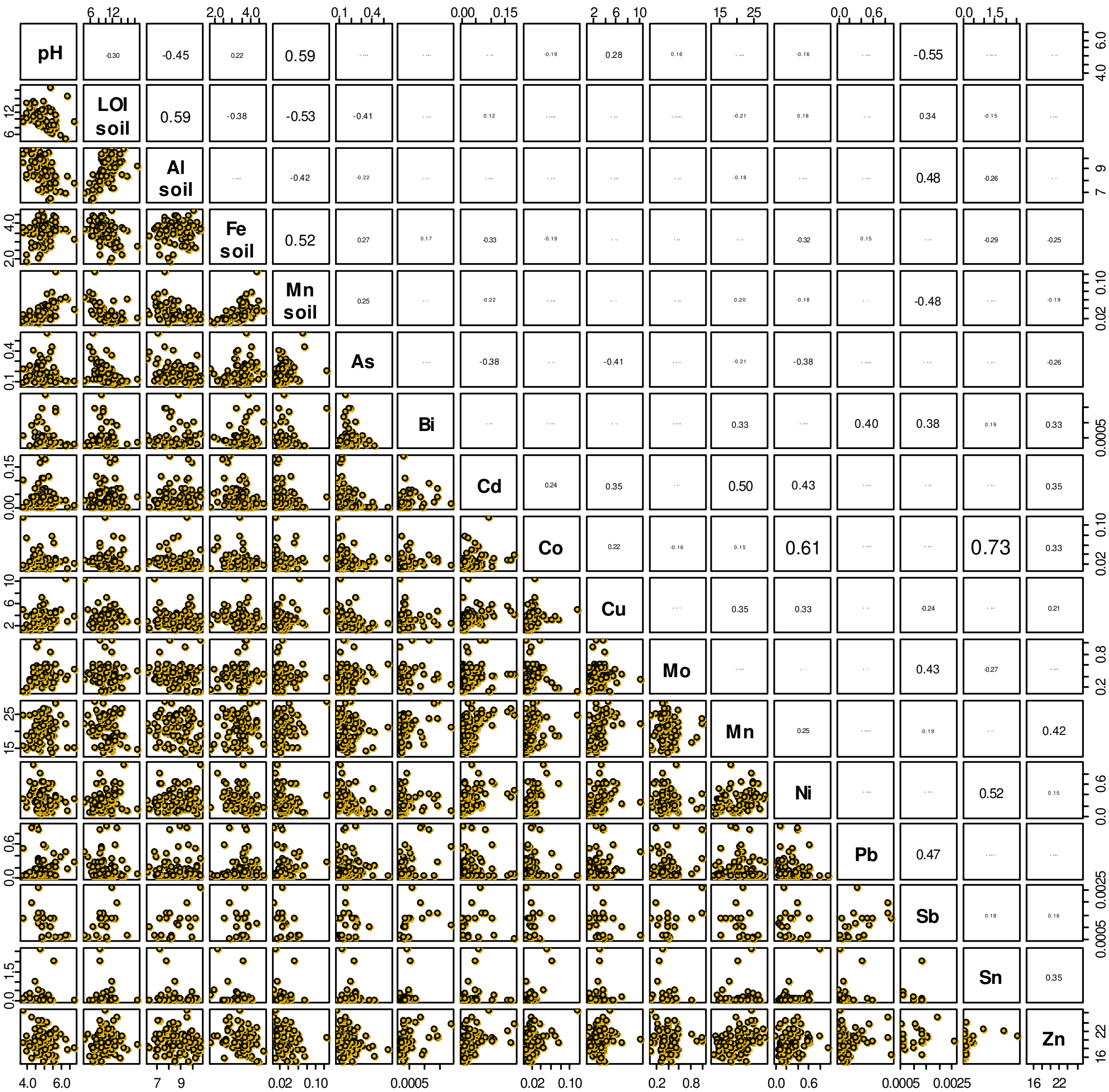


Fig. A2.3 Scattergram and correlation matrix of trace element concentrations in rice grains of the Mekong River Delta area including relations between grain concentrations and soil parameters (soil concentrations in wt. %, grain concentrations in mg kg^{-1})

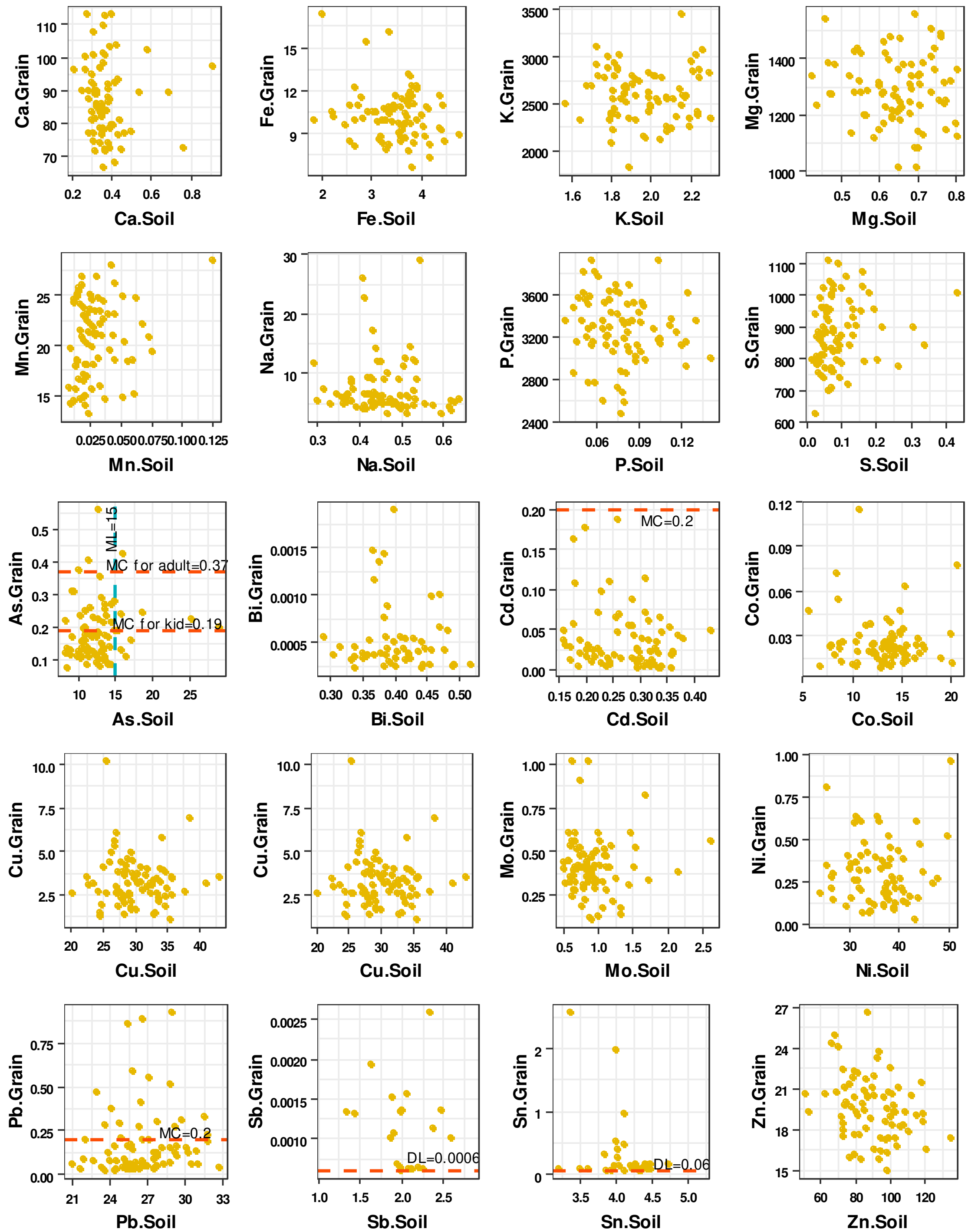


Fig. A2.4 Scattergrams of element concentrations in soils versus concentrations in corresponding grains in the Mekong River Delta area (main elements in soils in %, trace elements in soils and grains in mg kg^{-1}). For As, Cd, and Pb plots, red lines indicate the maximum level (ML) for Vietnamese agricultural soil. blue lines represent the maximum concentration (MC) of elements in rice grain for adults and children. The green lines in the plots of Sb and Sn represent their detection limit (DL).

Appendix A3: Supplementary Material for Chapter 5

Table A3.1 Coordinates of sample positions and mass ratios of plant parts to the aboveground plant

Area	Site	E	N	Mass ratio			Area	Site	E	N
				Shoot	Husk	Grain				
Huong	H1	107.5372	16.44096	0.52	0.10	0.38	Mekong	MK31	105.4434	10.55026
River	H5	107.5875	16.54479	0.42	0.11	0.47	River	MK32	105.4503	10.5412
	H6	107.5945	16.55145	0.49	0.10	0.41		MK33	105.4884	10.49884
	H7	107.5947	16.55188	0.45	0.11	0.44		MK34	105.4842	10.49025
Red	HN1	105.9115	20.85542	0.44	0.10	0.46		MK35	105.4921	10.49890
River	HN2	105.9049	20.8294	0.31	0.15	0.54		MK36	105.5078	10.46332
	HN3	105.9071	20.80671	0.35	0.13	0.52		MK37	105.4510	10.53349
	HN5	105.4479	21.18195	0.36	0.13	0.51		MK38	105.4103	10.53300
	HN6	105.4500	21.18146	0.47	0.13	0.40		MK40	105.4384	10.53296
	HN7	105.4522	21.18124	0.45	0.10	0.45		MK41	105.4269	10.53729
	HN8	105.4515	21.18280	0.62	0.15	0.23		MK42	105.4139	10.54031
	HN9	105.4506	21.18461	0.47	0.08	0.45		MK43	106.1629	10.15198
	HN10	105.3556	21.23928	0.40	0.11	0.49		MK44	106.1141	10.16194
	HN11	105.5521	21.17566	0.33	0.11	0.56		MK45	106.1052	10.16381
	PT1	105.0707	21.48281	0.39	0.12	0.49		MK46	106.0737	10.16444
	PT3	105.0672	21.49603	0.39	0.13	0.48		MK47	106.0812	10.16661
	PT4	105.1323	21.43983	0.40	0.12	0.48		MK48	105.0946	10.17084
	PT6	105.2812	21.34621	0.44	0.13	0.43		MK49	106.1047	10.18074
	PT7	105.2802	21.34854	0.43	0.08	0.49		MK51	105.3216	10.83619
	PT8	105.2794	21.35039	0.40	0.10	0.50		MK52	105.3270	10.84106
	PT9	105.2804	21.35107	0.35	0.12	0.53		MK53	105.3333	10.83933
	PT10	105.3543	21.31105	0.38	0.13	0.49		MK54	105.3181	10.82736
	PT11	105.4452	21.29736	0.43	0.11	0.46		MK55	105.3244	10.82386
Mekong	MK1	105.1789	10.84005					MK56	105.3239	10.82708
River	MK2	105.1726	10.83846					MK57	105.3321	10.82444
	MK3	105.2876	10.82348					MK58	105.3343	10.81592
	MK4	105.3117	10.83041					MK59	105.3526	10.79633
	MK5	105.3077	10.82734					MK60	105.3582	10.77364
	MK6	105.2991	10.82513					MK61	105.3770	10.52436
	MK7	105.3071	10.7954					MK62	105.3861	10.51619
	MK8	105.3047	10.79752					MK63	105.4013	10.50378
	MK9	105.3082	10.78972					MK64	105.3988	10.48869
	MK10	105.1407	10.7277					MK65	105.3840	10.43972
	MK11	105.2111	10.80318					MK66	105.3900	10.43422
	MK12	105.1952	10.79276					MK67	105.9468	9.877722
	MK13	105.1966	10.80347					MK68	105.9506	9.868500
	MK14	105.2539	10.16000					MK69	105.9633	9.862083
	MK15	105.2278	10.79780					MK70	105.9845	9.837694
	MK16	105.2187	10.80072					MK71	105.9907	9.832972
	MK17	105.2050	10.77340					MK72	106.0933	9.811639
	MK18	105.1952	10.77515					MK73	106.0785	9.825667
	MK19	105.2079	10.79831					MK74	106.0783	9.812667
	MK20	105.2653	10.76141					MK75	106.0711	9.846556
	MK21	105.2436	10.74276					MK76	105.6119	10.35236
	MK22	105.2535	10.68282					MK77	105.6144	10.35535
	MK23	105.2726	10.65025					MK78	105.6179	10.36672
	MK24	105.2934	10.62049					MK79	105.6466	10.38142
	MK25	105.3058	10.59924					MK80	105.7149	10.47660
	MK26	106.4413	10.35912					MK81	105.7232	10.49193
	MK27	106.4850	10.34935					MK82	105.8007	10.48096
	MK30	105.4629	10.43315							

Table A3.2 Measured element concentrations in husk and shoot (mg kg^{-1}; n = 23)

Site	Al		Ca		Fe		K		Mg		Mn		Na		P		S		As		Ba	
	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot
H1	32	246	730	4921	28	476	4777	32125	214	1411	152	684	3.7	146	1149	2660	688	2074	0.75	5.95	21.6	125
H5	32	29	2739	3106	60	132	5072	19173	1027	3626	198	966	11.8	1498	1222	537	407	1111	1.20	3.08	9.4	123
H6	32	41	790	4914	30	105	5228	15288	194	4931	379	1184	9.5	87	987	1312	596	3328	0.26	0.86	20.3	119
H7	46	56	1296	2709	45	158	5680	24764	234	2107	278	556	13.4	448	1057	1456	524	2884	0.92	3.14	35.4	135
HN1	93	924	1296	6038	98	612	9512	37541	584	3435	129	1185	43.2	874	1544	2264	689	1849	1.45	10.53	22.4	92
HN2	149	571	1018	7872	107	396	3227	42715	174	2735	140	574	25.0	178	1608	1147	562	1163	0.24	2.85	9.8	86
HN3	74	731	927	6478	68	475	3796	37939	242	3088	109	484	17.4	478	1526	1482	695	1068	0.43	4.20	9.2	55
HN5	62	105	991	7428	57	107	3202	31271	230	3407	169	667	13.7	42	985	979	791	1619	0.19	1.49	0.7	104
HN6	258	116	1495	3311	176	104	1230	39644	491	1895	317	610	36.6	103	1065	575	658	981	0.64	2.08	30.5	82
HN7	152	181	816	4016	99	161	2998	32866	244	2472	181	613	30.8	221	1259	619	412	1402	0.24	1.41	11.2	61
HN8	35	74	683	3087	39	77	3358	17291	210	2165	257	623	37.2	115	873	768	432	1341	0.17	0.78	17.2	96
HN9	62	199	812	4517	55	193	3723	31571	345	2634	257	1050	34.9	79	1009	1258	222	1385	0.18	3.86	19.8	123
HN10	79	63	956	4351	71	108	3635	40087	323	2480	217	2580	22.8	54	1235	1055	751	2625	0.12	1.79	31.1	62
HN11	42	182	956	4997	112	129	4916	57709	450	2179	193	637	29.0	161	1674	645	933	1483	0.68	3.69	14.3	72
PT1	29	44	1023	4835	59	64	5113	38050	516	2758	287	1158	18.3	145	1101	971	570	1835	0.58	0.43	28.1	133
PT3	23	14	1027	3131	33	38	2310	42162	275	2390	142	337	7.5	245	1135	588	708	1092	0.33	1.73	30.4	132
PT4	104	187	1089	5264	108	241	5238	39074	279	2703	54	89	26.0	40	989	821	959	1244	0.15	0.37	7.7	60
PT6	43	503	1837	2534	161	637	4159	21335	227	3687	156	617	53.2	1497	1567	2058	673	1736	0.62	3.95	24.3	71
PT7	21	122	811	8269	57	249	3049	21795	264	3786	242	336	37.6	347	1790	2318	709	2827	0.47	5.14	30.7	52
PT8	41	142	1187	4109	53	160	2511	33990	373	2587	259	547	11.9	186	1098	1644	777	1693	0.76	4.26	25.1	120
PT9	17	80	946	7037	38	98	2962	34367	287	1897	139	415	10.3	113	1272	397	732	1804	0.40	2.57	16.7	82
PT10	91	419	1948	6088	79	431	4587	48168	478	1866	1412	55	26.6	1846	1672	1209	884	1970	0.39	0.74	22.1	194
PT11	133	163	1187	5878	112	176	4555	30039	118	2974	214	650	29.8	166	1445	791	946	1906	0.26	1.09	23.4	118

Table A3.2 (*cont.*) Measured element concentrations in husk and shoot (mg kg^{-1}; n = 23)

Site	Bi		Cd		Ce		Co		Cr		Cs		Cu		Hf		La		Li		Mo	
	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot
H1	0.003	0.016	0.029	0.319	0.15	0.49	0.10	1.11	0.37	0.94	0.18	0.20	3.01	2.88	0.005	0.033	0.066	0.229	0.04	0.18	0.07	1.13
H5	0.009	0.003	0.489	0.978	0.05	0.33	0.09	0.73	0.47	0.69	0.13	0.77	2.70	3.55	0.002	0.010	0.029	0.158	0.03	0.07	0.07	0.13
H6	0.001	0.005	0.082	0.313	0.09	0.38	0.25	0.78	0.45	0.67	0.71	2.46	2.23	5.26	0.002	0.006	0.047	0.201	0.03	0.15	0.06	0.86
H7	0.002	0.010	0.021	0.183	0.04	0.17	0.09	0.61	0.34	0.79	0.60	0.86	0.92	2.50	0.004	0.005	0.023	0.090	0.01	0.14	0.04	0.73
HN1	0.010	0.026	0.002	0.168	0.14	1.10	0.07	0.37	0.57	2.37	0.21	0.55	2.60	3.00	0.010	0.054	0.073	0.550	0.07	0.64	0.08	0.74
HN2	0.008	0.019	0.020	0.105	0.47	2.02	0.06	0.31	0.29	2.25	0.05	0.62	1.47	4.11	0.019	0.061	0.231	1.057	0.12	0.40	0.04	0.69
HN3	0.010	0.024	0.003	0.111	0.14	0.88	0.04	0.33	0.33	1.69	0.04	0.71	1.21	2.61	0.010	0.063	0.073	0.447	0.07	0.60	0.03	1.22
HN5	0.005	0.009	0.016	0.145	0.09	0.27	0.04	0.16	0.22	1.07	0.05	0.07	1.94	3.51	0.003	0.021	0.045	0.188	0.02	0.11	0.07	0.32
HN6	0.008	0.010	0.776	0.177	0.37	0.13	0.08	0.22	0.50	1.02	0.04	0.09	1.64	2.11	0.025	0.015	0.189	0.151	0.17	0.09	0.09	0.37
HN7	0.005	0.008	0.020	0.385	0.19	0.20	0.05	0.16	0.25	1.11	0.05	0.08	1.40	3.13	0.009	0.017	0.101	0.102	0.09	0.11	0.03	0.43
HN8	0.003	0.005	0.103	0.721	0.07	0.17	0.03	0.10	0.19	1.07	0.07	0.10	3.05	3.00	0.006	0.016	0.035	0.053	0.04	0.13	0.05	0.21
HN9	0.006	0.012	0.215	1.332	0.09	0.34	0.05	0.23	0.84	0.77	0.12	0.03	1.80	3.80	0.004	0.016	0.049	0.170	0.04	0.16	0.32	0.08
HN10	0.003	0.005	0.680	3.395	0.12	0.22	0.06	0.27	0.49	0.93	0.04	0.13	2.70	6.07	0.006	0.016	0.059	0.084	0.05	0.14	0.06	0.10
HN11	0.005	0.010	0.036	0.195	0.13	0.32	0.14	0.20	1.03	1.09	0.03	0.05	3.95	4.10	0.010	0.017	0.061	0.156	0.04	0.14	0.06	1.19
PT1	0.007	0.007	0.012	0.461	0.11	0.06	0.10	0.06	0.24	0.84	0.08	0.13	2.97	3.76	0.009	0.009	0.051	0.026	0.07	0.12	0.10	1.34
PT3	0.008	0.003	0.019	0.114	0.07	0.03	0.02	0.12	0.44	0.83	0.08	0.20	2.90	3.03	0.005	0.010	0.038	0.020	0.06	0.05	0.05	0.58
PT4	0.018	0.011	0.015	0.120	0.33	0.38	0.05	0.10	0.63	0.81	0.03	0.37	2.53	10.54	0.010	0.014	0.210	0.232	0.08	0.16	0.13	0.70
PT6	0.011	0.014	0.002	0.088	0.70	0.41	0.15	0.27	0.61	1.88	0.31	0.40	3.15	1.70	0.029	0.012	0.347	0.576	0.22	0.30	0.10	0.12
PT7	0.001	0.016	0.003	0.105	0.06	0.26	0.33	0.45	0.42	0.95	0.58	0.35	4.05	1.28	0.002	0.005	0.035	0.127	0.02	0.15	0.34	0.48
PT8	0.007	0.011	0.005	0.198	0.07	0.17	0.04	0.42	0.37	1.02	0.05	0.08	0.43	3.02	0.004	0.015	0.040	0.086	0.03	0.11	0.07	0.48
PT9	0.005	0.014	0.002	0.113	0.08	0.18	0.03	0.14	0.54	1.11	0.02	0.04	1.04	2.58	0.004	0.007	0.052	0.092	0.04	0.06	0.07	0.30
PT10	0.005	0.013	0.001	0.061	0.16	0.48	0.19	0.24	0.26	1.48	0.23	0.11	2.62	5.67	0.008	0.032	0.085	0.233	0.08	0.26	0.09	0.12
PT11	0.007	0.011	0.037	0.361	0.19	0.47	0.06	0.18	0.72	0.78	0.05	0.05	2.02	2.68	0.011	0.024	0.094	0.243	0.07	0.15	0.05	0.39

Table A3.2 (*cont.*) Measured element concentrations in husk and shoot (mg kg^{-1}; n = 23)

Site	Ni		Pb		Rb		Sb		Sn		Sr		Th		Tl		Ti		U		Zn		Zr	
	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot	Husk	Shoot
H1	0.49	0.65	1.61	0.21	24	68	0.015	0.017	<0.06	<0.06	2.3	13.3	0.008	0.078	1.7	17.5	0.001	0.023	0.010	0.026	10.0	74	0.08	0.38
H5	0.37	0.50	0.66	0.12	48	145	0.021	0.007	<0.06	<0.06	7.6	15.5	0.008	0.018	1.8	4.3	0.007	0.163	0.004	0.006	9.3	90	0.05	0.11
H6	0.59	1.95	0.41	0.35	67	170	0.002	0.008	<0.06	<0.06	4.6	24.4	0.007	0.016	1.6	4.2	0.004	0.298	0.002	0.005	8.6	35	0.07	0.12
H7	0.35	0.51	0.32	0.06	58	195	0.002	0.010	<0.06	<0.06	6.2	12.0	0.007	0.018	1.7	4.7	0.001	0.097	0.004	0.009	10.2	52	0.14	0.16
HN1	0.47	1.14	1.72	1.12	5	14	0.052	0.097	<0.06	<0.06	4.6	21.4	0.029	0.198	7.1	54.2	0.007	0.020	0.011	0.166	13.0	28	0.38	1.71
HN2	0.42	0.64	0.58	1.09	16	68	0.024	0.051	<0.06	<0.06	3.2	23.8	0.093	0.223	12.9	49.3	0.005	0.022	0.012	0.038	6.5	49	0.71	1.81
HN3	0.19	0.69	0.96	1.47	11	48	0.025	0.068	<0.06	<0.06	3.4	21.4	0.032	0.176	7.8	52.0	0.005	0.030	0.007	0.039	6.4	34	0.38	1.71
HN5	0.18	0.37	0.39	0.67	12	42	0.025	0.019	<0.06	<0.06	3.3	19.0	0.014	0.047	1.9	12.4	0.003	0.009	0.007	0.009	2.0	32	0.12	0.43
HN6	0.97	0.17	0.53	0.77	13	72	0.019	0.027	<0.06	<0.06	6.3	8.6	0.061	0.030	17.5	7.9	0.006	0.014	0.020	0.008	22.7	51	0.56	1.28
HN7	0.31	0.33	0.31	0.72	11	59	0.010	0.024	<0.06	<0.06	2.7	9.4	0.033	0.035	9.4	9.6	0.004	0.014	0.009	0.009	6.8	54	0.33	0.28
HN8	0.36	0.36	0.27	0.71	15	40	0.009	0.015	<0.06	<0.06	3.0	9.5	0.011	0.020	3.1	5.7	0.003	0.011	0.003	0.005	10.4	31	0.25	1.25
HN9	1.25	0.47	0.40	1.41	5	23	0.016	0.028	5.18	7.82	2.6	13.8	0.016	0.053	4.1	15.4	0.003	0.010	0.006	0.015	12.4	69	0.15	1.11
HN10	0.89	0.69	0.77	0.56	13	64	0.021	0.010	1.58	3.31	5.8	11.1	0.022	0.030	5.3	6.7	0.003	0.010	0.007	0.009	16.5	12	0.24	0.30
HN11	1.04	0.93	2.96	1.33	9	47	0.011	0.029	0.53	1.83	3.0	10.7	0.039	0.075	3.9	14.4	0.004	0.018	0.017	0.019	6.3	69	0.43	0.88
PT1	0.34	0.59	2.58	0.17	32	165	0.098	0.184	<0.06	<0.06	4.6	17.4	0.034	0.064	6.4	3.0	0.005	0.019	0.017	0.002	18.0	71	0.37	0.33
PT3	0.25	0.12	0.40	0.21	41	221	0.014	0.007	<0.06	<0.06	4.5	11.3	0.019	0.014	3.1	1.1	0.005	0.040	0.003	0.003	10.2	33	0.12	0.06
PT4	0.29	0.37	0.83	0.72	7	42	0.018	0.020	<0.06	<0.06	2.5	10.7	0.062	0.137	10.6	12.9	0.007	0.009	0.010	0.010	11.4	28	0.36	0.41
PT6	0.55	0.43	2.35	0.68	28	93	0.066	0.033	<0.06	<0.06	6.7	10.1	0.140	0.374	6.6	25.2	0.008	0.017	0.036	0.025	7.6	15	1.08	0.44
PT7	1.60	0.60	0.67	0.99	31	61	0.001	0.037	<0.06	<0.06	4.5	24.2	0.018	0.060	2.2	7.4	0.001	0.012	0.013	0.009	40.6	10	0.09	0.19
PT8	0.17	0.33	0.53	0.79	26	64	0.017	0.028	<0.06	<0.06	4.2	13.8	0.011	0.035	2.9	8.5	0.004	0.015	0.005	0.008	1.8	68	0.16	0.30
PT9	0.18	0.22	0.48	1.07	12	49	0.011	0.033	<0.06	<0.06	3.6	21.2	0.014	0.016	4.1	4.5	0.004	0.015	0.003	0.007	2.3	42	0.12	0.13
PT10	2.11	0.84	0.80	1.00	7	23	0.038	0.027	2.12	5.01	4.5	24.4	0.027	0.090	7.2	24.0	0.005	0.010	0.011	0.039	10.8	16	0.32	1.32
PT11	0.41	0.34	0.80	1.32	12	40	0.019	0.027	2.86	3.11	4.2	13.7	0.033	0.076	9.3	20.4	0.005	0.014	0.011	0.016	15.1	55	0.38	0.48

Table A3.3 Physiological element concentrations (Con) in shoot (mg kg^{-1}) and their transfer factors (TF) (n = 23)

Site	Al		Ca		Fe		K		Mg		Mn		Na		P		S		As		Ba	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
H1	<4	<0.00005	4929	2.24	346	0.0090	32145	1.45	1393	0.22	685	2.62	137	0.053	2666	3.73	2079	3.72	5.9	0.474	123	0.25
H5	<4	<0.00005	3107	1.45	98	0.0025	19171	0.92	3623	0.58	967	3.46	1496	0.464	537	1.08	1112	2.32	3.1	0.182	123	0.25
H6	<4	<0.00005	4916	2.19	79	0.0028	15286	0.90	4930	1.00	1185	4.99	84	0.028	1313	3.17	3331	11.2	0.8	0.076	118	0.29
H7	<4	<0.00005	2710	1.33	128	0.0043	24768	1.37	2103	0.39	557	2.39	445	0.150	1457	3.89	2886	8.03	3.1	0.254	134	0.31
HN1	99	0.00133	6002	0.71	178	0.0045	37672	1.79	3370	0.38	1190	2.00	822	0.154	2279	2.70	1861	3.02	10.4	0.586	89	0.22
HN2	<4	<0.00005	7864	1.12	46	0.0014	42879	2.38	2677	0.36	571	0.79	123	0.023	1153	1.51	1172	7.17	2.7	0.174	82	0.22
HN3	<4	<0.00005	6464	1.02	92	0.0028	38081	2.08	3025	0.39	483	0.97	418	0.077	1491	1.92	1076	3.38	4.1	0.270	51	0.14
HN5	<4	<0.00005	7430	1.46	11	0.0003	31284	1.60	3392	0.40	667	1.28	28	0.005	979	1.15	1622	3.75	1.4	0.081	103	0.26
HN6	<4	<0.00005	3310	0.83	41	0.0010	39683	1.84	1885	0.21	610	0.76	95	0.018	575	0.84	982	3.47	2.1	0.086	82	0.19
HN7	26	0.00031	4017	1.26	84	0.0019	32882	1.38	2459	0.25	613	1.81	213	0.044	619	1.05	1404	4.20	1.4	0.070	60	0.14
HN8	<4	<0.00005	3087	1.05	31	0.0007	17284	0.74	2157	0.22	623	1.83	110	0.022	768	1.28	1342	3.77	0.8	0.039	95	0.22
HN9	<4	<0.00005	4519	1.29	74	0.0017	31584	1.36	2612	0.26	1052	3.20	65	0.013	1258	1.30	1387	3.50	3.8	0.229	123	0.27
HN10	<4	<0.00005	4353	1.77	31	0.0006	40112	1.95	2476	0.52	2583	12.5	50	0.016	1056	1.44	2627	2.64	1.7	0.057	61	0.17
HN11	<4	<0.00005	4996	1.10	7	0.0002	57774	2.45	2156	0.22	637	0.99	145	0.027	644	0.51	1486	5.92	3.6	0.165	71	0.16
PT1	<4	<0.00005	4835	1.04	48	0.0021	38074	3.28	2757	0.65	1159	3.56	141	0.024	971	1.03	1837	10.1	0.4	0.045	133	0.42
PT3	<4	<0.00005	3130	0.39	30	0.0008	42171	2.20	2389	0.26	337	0.60	243	0.032	588	0.56	1092	2.39	1.7	0.079	132	0.30
PT4	<4	<0.00005	5249	0.49	132	0.0032	39119	1.89	2683	0.26	88	0.11	20	0.003	821	0.92	1247	6.92	0.2	0.005	59	0.11
PT6	<4	<0.00005	2531	0.84	72	0.0008	21386	1.93	3680	0.84	618	1.44	1491	0.645	2067	3.48	1742	2.64	3.8	0.144	70	0.33
PT7	<4	<0.00005	8277	2.49	103	0.0013	21815	2.63	3786	1.11	336	1.15	344	0.175	2321	3.80	2830	4.26	5.1	0.282	52	0.33
PT8	15	0.00023	4102	0.58	90	0.0025	34011	1.82	2577	0.34	547	1.04	173	0.025	1645	1.55	1695	3.12	4.2	0.172	119	0.27
PT9	<4	<0.00005	7029	0.47	62	0.0017	34383	1.87	1889	0.20	415	0.57	107	0.017	396	0.30	1805	3.94	2.5	0.089	81	0.19
PT10	<4	<0.00005	6090	1.17	195	0.0039	48246	1.94	1826	0.18	53	0.08	1832	0.414	1212	1.47	1952	0.35	0.6	0.029	192	0.42
PT11	<4	<0.00005	5878	1.08	12	0.0003	30063	1.42	2959	0.46	650	1.12	155	0.048	791	0.93	1910	3.29	1.0	0.055	117	0.31

Table A3.3 *(cont.)* Physiological element concentrations (Con) in shoot (mg kg^{-1}) and their transfer factors (TF) (n = 23)

Site	Bi		Cd		Ce		Co		Cr		Cs		Cu		Hf		La		Li		Mo	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
H1	0.014	0.017	0.32	0.93	0.135	0.0013	1.05	0.061	0.78	0.017	0.172	0.0221	2.77	0.08	0.021	0.0063	0.068	0.0014	0.077	0.0026	1.13	1.02
H5	0.003	0.005	0.98	4.47	0.252	0.0028	0.72	0.050	0.66	0.015	0.764	0.1159	3.53	0.12	0.007	0.0018	0.119	0.0027	0.041	0.0014	0.13	0.11
H6	0.004	0.011	0.31	1.65	0.319	0.0051	0.77	0.078	0.64	0.021	2.461	0.5031	5.24	0.26	0.002	0.0005	0.169	0.0049	0.129	0.0060	0.86	1.06
H7	0.009	0.021	0.18	0.90	0.102	0.0015	0.60	0.055	0.76	0.023	0.851	0.1570	2.48	0.11	0.001	0.0003	0.053	0.0015	0.114	0.0049	0.73	0.79
HN1	0.020	0.040	0.17	0.48	0.205	0.0025	0.18	0.011	1.74	0.030	0.454	0.0519	2.61	0.07	0.001	0.0001	0.087	0.0021	0.154	0.0035	0.74	1.06
HN2	0.014	0.033	0.10	0.34	1.196	0.0152	0.17	0.012	1.76	0.037	0.554	0.0808	3.79	0.11	0.008	0.0015	0.643	0.0163	0.022	0.0006	0.69	1.69
HN3	0.019	0.041	0.11	0.32	0.062	0.0009	0.17	0.012	1.10	0.022	0.632	0.0901	2.18	0.06	0.012	0.0029	0.022	0.0006	0.170	0.0047	1.22	2.91
HN5	0.008	0.021	0.14	0.39	0.071	0.0009	0.11	0.007	0.92	0.015	0.054	0.0067	3.42	0.09	0.010	0.0021	0.091	0.0023	0.007	0.0002	0.32	0.60
HN6	0.009	0.022	0.18	0.47	0.004	0.0001	0.19	0.010	0.92	0.014	0.078	0.0085	2.06	0.05	0.008	0.0018	0.088	0.0021	0.022	0.0005	0.37	0.55
HN7	0.007	0.016	0.39	1.19	0.037	0.0004	0.13	0.007	0.98	0.013	0.066	0.0061	3.06	0.08	0.009	0.0021	0.021	0.0005	0.020	0.0004	0.43	0.68
HN8	0.005	0.010	0.72	2.34	0.069	0.0007	0.08	0.004	0.99	0.012	0.093	0.0087	2.95	0.07	0.011	0.0023	0.005	0.0001	0.072	0.0014	0.21	0.34
HN9	0.011	0.019	1.33	3.61	0.073	0.0008	0.18	0.009	0.51	0.005	0.003	0.0003	3.69	0.08	0.003	0.0007	0.040	0.0008	0.019	0.0004	0.08	0.15
HN10	0.004	0.008	3.40	10.6	0.085	0.0009	0.25	0.020	0.83	0.011	0.113	0.0106	6.02	0.16	0.009	0.0020	0.021	0.0005	0.080	0.0019	0.10	0.07
HN11	0.009	0.014	0.19	0.61	0.073	0.0008	0.15	0.008	0.90	0.013	0.018	0.0018	3.99	0.09	0.005	0.0011	0.036	0.0008	0.007	0.0001	1.19	1.72
PT1	0.007	0.015	0.46	1.93	0.009	0.0001	0.06	0.008	0.82	0.026	0.124	0.0390	3.75	0.13	0.006	0.0013	0.003	0.0001	0.109	0.0059	1.34	2.89
PT3	0.002	0.003	0.11	0.24	0.007	0.0001	0.12	0.008	0.82	0.016	0.199	0.0332	3.02	0.06	0.009	0.0019	0.009	0.0002	0.044	0.0013	0.58	0.74
PT4	0.001	0.000	0.12	0.21	0.088	0.0008	0.06	0.004	0.67	0.012	0.352	0.0540	10.4	0.12	0.003	0.0008	0.097	0.0019	0.077	0.0024	0.70	0.52
PT6	0.010	0.016	0.09	0.23	0.041	0.0007	0.20	0.018	1.10	0.009	0.376	0.0799	1.35	0.02	0.000	0.0001	0.376	0.0115	0.161	0.0072	0.10	0.05
PT7	0.015	0.024	0.10	0.51	0.121	0.0016	0.44	0.055	0.72	0.006	0.346	0.0937	1.21	0.03	0.002	0.0012	0.060	0.0016	0.115	0.0061	0.47	0.20
PT8	0.009	0.007	0.20	0.43	0.019	0.0003	0.39	0.027	0.91	0.016	0.071	0.0114	2.91	0.05	0.008	0.0024	0.013	0.0003	0.044	0.0013	0.48	0.55
PT9	0.012	0.008	0.11	0.23	0.096	0.0012	0.13	0.009	1.05	0.018	0.031	0.0047	2.52	0.04	0.003	0.0009	0.052	0.0013	0.029	0.0008	0.30	0.38
PT10	0.010	0.013	0.06	0.13	0.018	0.0002	0.15	0.007	1.06	0.012	0.057	0.0051	5.45	0.11	0.012	0.0027	0.011	0.0002	0.005	0.0001	0.11	0.09
PT11	0.009	0.014	0.36	0.74	0.067	0.0006	0.12	0.008	0.55	0.009	0.013	0.0012	2.54	0.07	0.010	0.0026	0.069	0.0015	0.010	0.0003	0.38	0.37

Table A3.3 *(cont.)* Physiological element concentrations (Con) in shoot (mg kg^{-1}) and their transfer factors (TF) (n = 23)

Site	Ni		Pb		Rb		Sb		Sn		Sr		Th		Tl		U		Zn		Zr	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
H1	0.52	0.015	0.07	0.002	68	0.51	0.011	0.006	<0.06	<0.01	13.2	0.34	0.0004	0.00002	0.021	0.030	0.0082	0.00159	74	0.64	0.049	0.00051
H5	0.47	0.015	0.10	0.003	145	1.18	0.006	0.003	<0.06	<0.01	15.5	0.37	0.0010	0.00005	0.162	0.258	0.0024	0.00051	90	1.06	0.014	0.00013
H6	1.93	0.090	0.33	0.014	170	1.74	0.007	0.005	<0.06	<0.01	24.4	0.61	0.0008	0.00005	0.298	0.611	0.0009	0.00023	35	0.55	0.005	0.00004
H7	0.48	0.020	0.03	0.001	196	1.86	0.009	0.006	<0.06	<0.01	12.0	0.30	0.0012	0.00007	0.097	0.182	0.0052	0.00132	52	0.75	0.054	0.00051
HN1	0.67	0.015	0.74	0.021	12	0.10	0.077	0.041	<0.06	<0.01	20.7	0.25	0.0077	0.00045	0.013	0.021	0.1258	0.03333	27	0.28	0.088	0.00060
HN2	0.27	0.008	0.77	0.025	67	0.62	0.034	0.021	<0.06	<0.01	23.2	0.31	0.0560	0.00355	0.016	0.031	0.0018	0.00052	48	0.57	0.173	0.00112
HN3	0.27	0.008	1.09	0.033	47	0.42	0.049	0.031	0.14	0.04	20.7	0.26	0.0081	0.00057	0.024	0.045	0.0027	0.00089	34	0.33	0.147	0.00111
HN5	0.27	0.006	0.59	0.017	42	0.36	0.014	0.008	<0.06	<0.01	18.9	0.26	0.0093	0.00061	0.008	0.014	0.0003	0.00008	32	0.33	0.075	0.00053
HN6	0.11	0.002	0.71	0.019	72	0.56	0.024	0.012	<0.06	<0.01	8.5	0.11	0.0051	0.00031	0.013	0.021	0.0028	0.00075	51	0.52	1.059	0.00695
HN7	0.24	0.005	0.64	0.016	59	0.41	0.020	0.011	<0.06	<0.01	9.2	0.12	0.0033	0.00019	0.013	0.018	0.0019	0.00051	54	0.51	0.020	0.00014
HN8	0.31	0.006	0.67	0.015	39	0.28	0.013	0.007	<0.06	<0.01	9.5	0.12	0.0013	0.00007	0.011	0.015	0.0006	0.00015	30	0.28	1.090	0.00716
HN9	0.33	0.007	1.29	0.029	22	0.16	0.022	0.011	7.83	1.76	13.6	0.17	0.0029	0.00016	0.008	0.011	0.0037	0.00093	68	0.62	0.691	0.00463
HN10	0.65	0.019	0.51	0.013	64	0.48	0.005	0.001	3.31	0.69	11.0	0.14	0.0037	0.00020	0.009	0.012	0.0027	0.00064	12	0.14	0.090	0.00060
HN11	0.81	0.018	1.22	0.029	47	0.33	0.024	0.013	1.82	0.35	10.5	0.13	0.0282	0.00169	0.016	0.023	0.0088	0.00240	69	0.52	0.480	0.00339
PT1	0.57	0.031	0.14	0.003	165	2.57	0.183	0.177	<0.06	<0.01	17.4	0.22	0.0545	0.00410	0.018	0.056	0.0001	0.00002	71	1.02	0.232	0.00163
PT3	0.11	0.003	0.19	0.003	221	2.09	0.007	0.004	<0.06	<0.01	11.3	0.12	0.0100	0.00060	0.040	0.075	0.0027	0.00078	33	0.32	0.020	0.00013
PT4	0.27	0.007	0.50	0.006	42	0.35	0.013	0.005	<0.06	<0.01	10.4	0.09	0.0941	0.00578	0.007	0.013	0.0002	0.00004	28	0.21	0.082	0.00064
PT6	0.26	0.010	0.34	0.006	93	1.43	0.025	0.018	<0.06	<0.01	10.0	0.28	0.2261	0.00930	0.015	0.039	0.0019	0.00051	14	0.10	0.072	0.00119
PT7	0.56	0.025	0.89	0.017	61	1.25	0.034	0.030	<0.06	<0.01	24.2	0.81	0.0052	0.00017	0.012	0.038	0.0011	0.00027	10	0.12	0.104	0.00223
PT8	0.27	0.008	0.65	0.009	64	0.62	0.024	0.011	<0.06	<0.01	13.7	0.14	0.0066	0.00044	0.014	0.025	0.0014	0.00043	68	0.60	0.079	0.00070
PT9	0.19	0.005	0.98	0.011	49	0.45	0.031	0.015	<0.06	<0.01	21.2	0.21	0.0005	0.00003	0.015	0.028	0.0042	0.00135	42	0.33	0.014	0.00013
PT10	0.59	0.011	0.77	0.016	22	0.15	0.019	0.011	5.00	0.95	24.2	0.30	0.0039	0.00021	0.006	0.008	0.0194	0.00458	15	0.10	0.650	0.00457
PT11	0.19	0.005	1.14	0.023	40	0.30	0.016	0.006	3.10	0.46	13.6	0.32	0.0056	0.00031	0.011	0.016	0.0001	0.00003	54	0.44	0.020	0.00017

Table A3.4 Physiological element concentrations (Con) in husk (mg kg^{-1}) and their transfer factors (TF) (n = 101)

Site	Al		Ca		Fe		K		Mg		Mn		Na		P		S		As		Ba	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
H1	<4	<0.00005	729	0.33	15	0.0004	4772	0.22	212	0.03	152	0.58	3	0.0011	1149	1.61	688	1.23	0.75	0.060	21.4	0.044
H5	<4	<0.00005	2739	1.27	45	0.0011	5066	0.24	1026	0.16	198	0.71	11	0.0033	1222	2.45	407	0.85	1.20	0.071	9.3	0.019
H6	11	0.00018	789	0.35	20	0.0007	5224	0.31	192	0.04	379	1.60	8	0.0028	987	2.38	596	2.00	0.25	0.023	20.1	0.050
H7	22	0.00035	1295	0.64	34	0.0011	5676	0.31	232	0.04	278	1.19	12	0.0042	1057	2.82	524	1.46	0.91	0.074	35.3	0.082
HN1	<4	<0.00005	1286	0.15	41	0.0010	9495	0.45	572	0.07	128	0.22	36	0.0066	1545	1.83	689	1.12	1.43	0.080	21.8	0.055
HN2	<4	<0.00005	1001	0.14	16	0.0005	3186	0.18	154	0.02	138	0.19	10	0.0019	1610	2.10	563	3.45	0.20	0.013	8.7	0.023
HN3	<4	<0.00005	917	0.14	11	0.0003	3771	0.21	229	0.03	108	0.22	8	0.0015	1527	1.96	695	2.18	0.40	0.027	8.6	0.023
HN5	36	0.0005	989	0.19	43	0.0011	3196	0.16	227	0.03	169	0.32	12	0.0022	985	1.16	791	1.83	0.18	0.010	0.5	0.001
HN6	8	0.00010	1486	0.37	37	0.0009	1164	0.05	463	0.05	315	0.39	20	0.0038	1066	1.55	659	2.33	0.57	0.024	29.3	0.069
HN7	<4	<0.00005	812	0.26	23	0.0005	2961	0.12	227	0.02	180	0.53	22	0.0047	1260	2.13	412	1.24	0.21	0.010	10.5	0.024
HN8	<4	<0.00005	682	0.23	14	0.0003	3347	0.14	205	0.02	257	0.75	34	0.0068	873	1.46	432	1.21	0.15	0.008	16.9	0.039
HN9	<4	<0.00005	810	0.23	23	0.0005	3708	0.16	338	0.03	257	0.78	31	0.0063	1009	1.05	222	0.56	0.17	0.010	19.4	0.043
HN10	<4	<0.00005	954	0.39	10	0.0002	3616	0.18	318	0.07	217	1.05	19	0.0062	1236	1.69	751	0.75	0.09	0.003	30.7	0.087
HN11	<4	<0.00005	953	0.21	79	0.0018	4901	0.21	443	0.05	193	0.30	25	0.0046	1674	1.33	933	3.72	0.66	0.030	13.9	0.031
PT1	<4	<0.00005	1017	0.22	24	0.0010	5103	0.44	511	0.12	287	0.88	10	0.0017	1101	1.17	571	3.14	0.56	0.059	27.7	0.088
PT3	<4	<0.00005	1022	0.13	9	0.0002	2299	0.12	270	0.03	142	0.25	3	0.0003	1135	1.07	708	1.55	0.32	0.014	30.1	0.069
PT4	<4	<0.00005	1068	0.10	19	0.0004	5204	0.25	257	0.03	52	0.07	10	0.0013	989	1.11	961	5.33	0.05	0.001	6.6	0.013
PT6	<4	<0.00005	1835	0.61	13	0.0001	4148	0.37	220	0.05	156	0.36	50	0.0214	1569	2.64	673	1.02	0.58	0.022	24.0	0.115
PT7	<4	<0.00005	810	0.24	14	0.0002	3046	0.37	262	0.08	242	0.83	37	0.0186	1791	2.93	709	1.07	0.46	0.026	30.6	0.192
PT8	<4	<0.00005	1184	0.17	30	0.0008	2500	0.13	368	0.05	258	0.49	7	0.0011	1098	1.04	777	1.43	0.75	0.030	24.9	0.057
PT9	<4	<0.00005	933	0.06	4	0.0001	2947	0.16	278	0.03	138	0.19	4	0.0007	1272	0.95	732	1.60	0.37	0.013	16.3	0.038
PT10	<4	<0.00005	1944	0.37	8	0.0002	4558	0.18	464	0.05	1413	2.13	20	0.0046	1673	2.03	877	0.16	0.36	0.016	21.5	0.047
PT11	<4	<0.00005	1180	0.22	37	0.0009	4526	0.21	107	0.02	213	0.37	24	0.0076	1446	1.69	946	1.63	0.23	0.012	22.8	0.061
MK1	<4	<0.00005	386	0.05	7	0.0002	3128	0.17	211	0.03	93	0.15	42	0.0101	789	1.21	409	0.57	0.09	0.007	2.6	0.006
MK2	<4	<0.00005	825	0.21	8	0.0002	5298	0.24	246	0.03	190	0.74	86	0.0225	1562	3.23	960	2.03	0.43	0.033	8.1	0.018
MK3	<4	<0.00005	607	0.15	13	0.0003	3483	0.17	225	0.03	153	0.50	51	0.0095	1360	1.97	426	0.95	0.13	0.011	9.2	0.022
MK4	<4	<0.00005	508	0.11	6	0.0002	4090	0.22	149	0.02	167	0.27	35	0.0056	1388	2.62	367	1.19	0.10	0.008	5.5	0.015
MK5	<4	<0.00005	540	0.15	6	0.0001	5792	0.27	302	0.04	133	0.22	31	0.0055	1144	1.77	565	1.89	0.15	0.010	6.6	0.016
MK6	<4	<0.00005	717	0.17	6	0.0002	8342	0.46	245	0.03	214	0.32	59	0.0093	1246	2.14	586	3.89	0.09	0.006	7.5	0.021
MK7	<4	<0.00005	829	0.21	17	0.0005	4822	0.26	444	0.07	158	0.50	157	0.0298	1674	3.02	391	0.94	0.35	0.027	8.2	0.021
MK8	<4	<0.00005	623	0.18	21	0.0005	4065	0.22	302	0.04	208	0.17	72	0.0134	1261	1.53	633	2.63	0.15	0.005	17.1	0.041
MK9	<4	<0.00005	433	0.12	4	0.0001	3583	0.16	171	0.02	197	0.49	25	0.0051	1267	1.56	325	0.69	0.39	0.016	2.5	0.005
MK10	<4	<0.00005	656	0.17	28	0.0007	2732	0.12	148	0.02	104	0.49	26	0.0065	1856	2.10	536	0.57	0.53	0.041	2.3	0.005
MK11	17	0.000272	677	0.19	30	0.0009	2840	0.17	304	0.05	253	0.75	27	0.0043	1311	1.06	476	0.90	0.46	0.049	3.9	0.011
MK12	<4	<0.00005	654	0.17	16	0.0004	4441	0.23	456	0.06	220	0.29	27	0.0045	1400	2.38	805	3.14	0.67	0.042	5.7	0.014
MK13	<4	<0.00005	752	0.24	13	0.0003	3337	0.16	208	0.03	156	0.45	22	0.0047	1723	1.94	593	1.44	0.31	0.022	3.2	0.008
MK14	<4	<0.00005	654	0.20	20	0.0006	4085	0.23	161	0.03	157	0.69	23	0.0044	1466	2.56	115	0.20	0.47	0.051	4.8	0.014

Table A3.4 (*cont.*) Physiological element concentrations (Con) in husk (mg kg^{-1}) and their transfer factors (TF) (n = 101)

Site	Al		Ca		Fe		K		Mg		Mn		Na		P		S		As		Ba	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
MK15	<4	<0.00005	798	0.22	10	0.0003	6406	0.35	727	0.10	260	0.58	60	0.0096	941	1.25	500	0.97	0.53	0.039	4.8	0.013
MK16	<4	<0.00005	763	0.18	18	0.0005	5827	0.32	661	0.09	166	0.32	27	0.0044	884	1.13	285	0.89	0.21	0.015	10.9	0.029
MK17	<4	<0.00005	735	0.19	5	0.0001	2735	0.15	127	0.02	246	0.48	21	0.0039	1434	1.19	282	0.68	0.26	0.017	4.6	0.013
MK18	<4	<0.00005	506	0.16	21	0.0005	1839	0.08	310	0.04	148	0.53	13	0.0028	1609	1.55	788	1.02	0.23	0.015	2.4	0.006
MK19	17	0.000241	876	0.22	56	0.0015	8625	0.47	1111	0.16	199	0.27	57	0.0100	1688	1.19	778	2.62	0.17	0.013	4.5	0.012
MK20	<4	<0.00005	654	0.20	18	0.0004	3703	0.19	264	0.04	191	0.46	36	0.0070	1316	1.30	468	0.96	0.54	0.041	8.9	0.022
MK21	<4	<0.00005	861	0.24	15	0.0005	3301	0.18	357	0.06	208	1.05	22	0.0044	1642	1.78	588	0.90	0.35	0.033	9.1	0.025
MK22	<4	<0.00005	692	0.17	13	0.0004	2891	0.16	143	0.03	309	1.64	28	0.0075	1881	2.20	1029	1.48	0.14	0.013	19.1	0.047
MK23	<4	<0.00005	778	0.13	4	0.0002	3841	0.23	153	0.03	83	0.49	31	0.0093	1120	1.67	900	0.59	0.18	0.017	13.5	0.033
MK24	<4	<0.00005	848	0.20	19	0.0006	3720	0.20	336	0.06	152	0.77	27	0.0071	1483	1.99	1055	1.42	0.25	0.021	13.8	0.033
MK25	<4	<0.00005	748	0.20	17	0.0006	2551	0.14	183	0.03	204	1.39	23	0.0048	1283	1.95	839	1.22	0.17	0.020	12.0	0.030
MK26	<4	<0.00005	739	0.24	16	0.0003	5285	0.25	541	0.08	156	0.48	42	0.0113	1364	1.74	583	0.94	0.32	0.026	4.9	0.016
MK27	<4	<0.00005	961	0.31	23	0.0006	6401	0.33	588	0.09	455	1.06	44	0.0098	1448	3.71	573	0.90	0.21	0.020	11.6	0.037
MK30	<4	<0.00005	928	0.35	37	0.0009	3372	0.15	165	0.02	120	0.66	33	0.0075	1116	1.95	966	1.52	0.37	0.031	23.8	0.053
MK31	<4	<0.00005	757	0.22	19	0.0004	4601	0.22	365	0.05	190	0.54	41	0.0084	1575	1.40	556	1.13	0.48	0.032	12.5	0.030
MK32	<4	<0.00005	675	0.23	10	0.0003	3128	0.15	399	0.05	109	0.47	32	0.0068	1328	1.75	426	0.76	0.58	0.050	11.7	0.028
MK33	<4	<0.00005	945	0.32	40	0.0011	2789	0.13	402	0.05	136	0.65	34	0.0074	1089	1.21	419	0.58	0.42	0.040	10.7	0.025
MK34	<4	<0.00005	710	0.21	12	0.0003	4389	0.22	308	0.04	244	0.97	27	0.0056	1094	1.38	316	0.57	0.08	0.007	9.1	0.022
MK35	<4	<0.00005	849	0.23	13	0.0003	3481	0.17	483	0.07	216	0.75	117	0.0215	977	0.84	445	0.37	0.25	0.023	2.4	0.006
MK36	<4	<0.00005	911	0.26	19	0.0005	2637	0.13	371	0.06	199	1.15	34	0.0094	1360	1.29	1125	1.25	0.07	0.005	4.4	0.011
MK37	<4	<0.00005	747	0.26	6	0.0002	3351	0.17	159	0.02	212	0.83	31	0.0062	1601	2.04	250	0.68	0.18	0.016	15.8	0.041
MK38	<4	<0.00005	601	0.16	8	0.0003	4169	0.20	473	0.07	84	0.35	24	0.0060	572	0.71	575	1.25	0.20	0.018	3.5	0.008
MK40	<4	<0.00005	971	0.22	29	0.0009	3748	0.17	459	0.07	254	1.12	8	0.0020	857	0.82	860	1.24	0.51	0.046	6.5	0.015
MK41	9	0.00009	590	0.18	5	0.0001	1869	0.09	541	0.07	110	0.46	28	0.0066	1693	2.02	620	0.61	0.24	0.018	4.2	0.010
MK42	70	0.00085	752	0.18	39	0.0011	5725	0.30	357	0.05	198	0.84	39	0.0078	1764	2.12	938	0.78	0.21	0.015	5.9	0.015
MK43	<4	<0.00005	701	0.24	25	0.0011	3232	0.19	248	0.05	203	1.62	31	0.0058	1249	2.48	499	0.64	0.23	0.025	9.9	0.026
MK44	<4	<0.00005	872	0.29	34	0.0013	3212	0.15	110	0.02	103	1.14	74	0.0176	840	1.88	775	0.81	0.50	0.048	6.5	0.016
MK45	<4	<0.00005	1112	0.32	38	0.0014	3770	0.21	164	0.03	197	1.46	64	0.0140	1692	2.75	487	0.37	0.53	0.049	4.2	0.011
MK46	<4	<0.00005	934	0.34	27	0.0015	2663	0.14	244	0.05	80	0.65	44	0.0088	1369	2.67	818	0.43	0.36	0.043	3.3	0.009
MK47	<4	<0.00005	748	0.21	9	0.0003	4087	0.21	304	0.05	237	0.74	42	0.0084	1299	1.84	473	0.23	0.95	0.051	4.9	0.013
MK48	<4	<0.00005	1300	0.42	16	0.0008	3516	0.20	127	0.03	163	2.22	140	0.0261	1459	3.12	1053	0.81	0.72	0.078	5.2	0.015
MK49	52	0.00054	646	0.24	28	0.0010	3317	0.17	286	0.05	103	1.08	38	0.0087	1729	2.32	1522	1.07	0.26	0.024	2.1	0.005
MK51	6	0.00009	784	0.26	35	0.0011	2656	0.17	332	0.06	108	0.42	44	0.0094	1511	2.33	526	1.44	0.40	0.040	9.4	0.029
MK52	<4	<0.00005	761	0.14	19	0.0005	5220	0.26	232	0.04	121	0.22	71	0.0165	1530	1.86	540	0.18	0.07	0.006	0.5	0.001
MK53	<4	<0.00005	611	0.17	15	0.0004	3607	0.17	212	0.03	115	0.58	54	0.0125	1479	2.20	652	0.39	0.16	0.013	1.6	0.004
MK54	<4	<0.00005	760	0.24	17	0.0005	3173	0.16	252	0.04	197	0.99	22	0.0053	1418	2.44	545	0.75	0.18	0.016	8.9	0.022
MK55	<4	<0.00005	910	0.24	21	0.0005	5420	0.24	538	0.07	142	0.51	49	0.0128	1678	2.39	498	0.56	0.29	0.021	1.6	0.004

Table A3.4 (*cont.*) Physiological element concentrations (Con) in husk (mg kg^{-1}) and their transfer factors (TF) (n = 101)

Site	Al		Ca		Fe		K		Mg		Mn		Na		P		S		As		Ba	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
MK56	<4	<0.00005	780	0.18	2	0.0001	6562	0.29	313	0.04	125	0.45	72	0.0209	1427	1.56	846	0.94	0.21	0.016	7.8	0.017
MK57	<4	<0.00005	715	0.20	1	0.0000	3892	0.21	430	0.07	142	0.32	60	0.0132	1424	2.61	1230	3.44	0.22	0.015	15.1	0.038
MK58	<4	<0.00005	839	0.26	8	0.0002	3671	0.19	416	0.07	170	0.63	40	0.0097	1581	2.91	310	0.56	0.15	0.010	18.7	0.047
MK59	<4	<0.00005	830	0.09	11	0.0004	4084	0.22	263	0.04	79	0.21	28	0.0065	1349	1.42	707	1.01	0.12	0.012	2.0	0.005
MK60	<4	<0.00005	782	0.21	0	0.0000	781	0.04	249	0.04	196	0.44	28	0.0062	1618	1.85	333	0.69	0.29	0.023	8.3	0.020
MK61	<4	<0.00005	577	0.16	9	0.0003	4111	0.23	130	0.02	225	0.50	22	0.0042	1482	1.86	503	1.52	0.13	0.010	17.0	0.045
MK62	<4	<0.00005	580	0.16	0	0.0000	1746	0.10	232	0.04	159	0.55	21	0.0049	1357	1.45	387	0.95	0.07	0.007	12.2	0.032
MK63	<4	<0.00005	1008	0.24	47	0.0013	5811	0.31	232	0.04	139	0.26	106	0.0241	1729	1.53	59	0.14	0.24	0.017	14.6	0.037
MK64	<4	<0.00005	733	0.34	88	0.0025	2913	0.14	261	0.04	224	1.84	14	0.0032	1977	3.86	679	0.43	0.13	0.009	1.0	0.002
MK65	<4	<0.00005	721	0.25	27	0.0008	4645	0.21	160	0.02	118	0.56	48	0.0134	1528	2.85	397	0.15	0.14	0.012	9.3	0.022
MK66	<4	<0.00005	999	0.26	20	0.0005	3336	0.15	422	0.06	218	0.84	28	0.0072	1476	3.36	585	0.17	0.40	0.028	2.2	0.005
MK67	<4	<0.00005	976	0.32	60	0.0021	6759	0.29	166	0.03	311	1.96	158	0.0359	1523	2.04	1237	1.64	0.15	0.016	6.0	0.016
MK68	<4	<0.00005	1018	0.31	50	0.0020	4347	0.19	324	0.05	359	1.97	127	0.0286	1385	1.68	728	0.85	0.19	0.022	9.3	0.025
MK69	<4	<0.00005	657	0.21	20	0.0008	3052	0.14	308	0.05	207	1.24	104	0.0240	1381	1.56	699	0.83	0.13	0.016	5.7	0.015
MK70	<4	<0.00005	849	0.25	12	0.0003	4484	0.20	481	0.07	145	0.44	116	0.0284	1321	1.58	467	0.60	2.54	0.184	3.2	0.008
MK71	<4	<0.00005	768	0.15	41	0.0011	5889	0.27	226	0.03	169	0.55	156	0.0376	1915	1.83	653	0.56	0.15	0.012	4.3	0.011
MK72	<4	<0.00005	617	0.13	19	0.0006	3907	0.22	240	0.05	94	0.58	156	0.0306	1418	1.15	592	0.62	0.15	0.012	0.5	0.002
MK73	<4	<0.00005	580	0.16	20	0.0006	3199	0.17	212	0.04	132	0.58	114	0.0226	1483	1.62	383	0.39	0.20	0.014	1.2	0.004
MK74	<4	<0.00005	710	0.10	13	0.0004	2701	0.15	285	0.06	240	1.49	136	0.0261	1731	1.38	382	0.31	0.20	0.017	0.9	0.003
MK75	<4	<0.00005	708	0.28	22	0.0008	2359	0.14	540	0.12	274	0.77	70	0.0136	1941	3.30	933	0.92	0.26	0.029	4.6	0.016
MK76	<4	<0.00005	712	0.20	12	0.0005	3754	0.21	363	0.07	106	0.83	38	0.0121	1435	1.79	729	0.46	0.26	0.023	5.7	0.014
MK77	<4	<0.00005	625	0.18	18	0.0005	4904	0.26	611	0.10	74	0.38	22	0.0048	1224	1.75	783	0.70	0.10	0.008	2.3	0.006
MK78	<4	<0.00005	612	0.18	19	0.0006	3958	0.20	343	0.05	91	0.45	32	0.0085	1914	2.50	755	0.97	0.21	0.017	12.6	0.029
MK79	<4	<0.00005	676	0.21	18	0.0005	4728	0.24	646	0.10	140	0.99	58	0.0197	1006	1.40	819	0.46	0.20	0.012	4.3	0.009
MK80	<4	<0.00005	653	0.21	25	0.0009	3434	0.19	134	0.03	374	2.46	38	0.0125	1034	1.91	761	0.58	0.11	0.010	6.9	0.018
MK81	<4	<0.00005	485	0.15	24	0.0006	4593	0.25	355	0.06	91	0.41	39	0.0106	1234	1.78	480	0.22	0.20	0.012	1.5	0.004
MK82	<4	<0.00005	848	0.24	21	0.0010	4874	0.28	328	0.08	172	1.17	34	0.0093	1365	1.05	541	0.13	0.13	0.013	0.8	0.002

Table A3.4 *(cont.)* Physiological element concentrations (Con) in husk (mg kg^{-1}) and their transfer factors (TF) (n = 101)

Site	Bi		Cd		Ce		Co		Cr		Cs		Cu		Hf		La		Li		Mo	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
H1	0.0024	0.0030	0.029	0.083	0.1132	0.001098	0.091	0.0052	0.35	0.0076	0.176	0.0227	3.00	0.087	0.0038	0.00112	0.0498	0.001053	0.0299	0.00100	0.07	0.06
H5	0.0085	0.0141	0.489	2.232	0.0221	0.000248	0.084	0.0058	0.45	0.0107	0.127	0.0192	2.69	0.092	0.0006	0.00016	0.0125	0.000278	0.0220	0.00076	0.07	0.06
H6	0.0008	0.0019	0.082	0.432	0.0632	0.001003	0.247	0.0249	0.44	0.0144	0.711	0.1454	2.23	0.110	0.0007	0.00018	0.0349	0.001019	0.0251	0.00117	0.06	0.07
H7	0.0023	0.0051	0.021	0.102	0.0162	0.000238	0.083	0.0075	0.33	0.0099	0.597	0.1101	0.91	0.040	0.0030	0.00081	0.0096	0.000265	0.0039	0.00017	0.04	0.04
HN1	0.0092	0.0181	0.002	0.004	0.0222	0.000275	0.049	0.0029	0.49	0.0084	0.202	0.0231	2.55	0.067	0.0031	0.00064	0.0122	0.000290	0.0023	0.00005	0.08	0.11
HN2	0.0069	0.0162	0.020	0.065	0.2523	0.003196	0.021	0.0015	0.16	0.0033	0.029	0.0043	1.38	0.041	0.0045	0.00090	0.1217	0.003086	0.0248	0.00069	0.04	0.09
HN3	0.0093	0.0203	0.002	0.006	0.0173	0.000248	0.016	0.0012	0.24	0.0047	0.028	0.0039	1.14	0.030	0.0025	0.00057	0.0097	0.000271	0.0096	0.00027	0.03	0.08
HN5	0.0048	0.0120	0.016	0.044	0.0591	0.000745	0.038	0.0022	0.20	0.0031	0.048	0.0060	1.93	0.049	0.0014	0.00032	0.0305	0.000782	0.0057	0.00013	0.07	0.12
HN6	0.0063	0.0157	0.777	2.086	0.0818	0.000933	0.019	0.0010	0.28	0.0043	0.011	0.0012	1.52	0.040	0.0099	0.00209	0.0507	0.001189	0.0221	0.00048	0.09	0.13
HN7	0.0044	0.0092	0.019	0.060	0.0323	0.000347	0.018	0.0010	0.11	0.0015	0.030	0.0028	1.33	0.033	0.0014	0.00030	0.0223	0.000493	0.0005	0.00001	0.03	0.05
HN8	0.0031	0.0064	0.103	0.335	0.0112	0.000118	0.016	0.0008	0.14	0.0018	0.063	0.0059	3.02	0.070	0.0034	0.00072	0.0084	0.000182	0.0054	0.00010	0.05	0.08
HN9	0.0055	0.0099	0.215	0.582	0.0224	0.000236	0.038	0.0019	0.77	0.0083	0.110	0.0105	1.77	0.039	0.0005	0.00011	0.0138	0.000296	0.0051	0.00010	0.32	0.61
HN10	0.0024	0.0046	0.680	2.112	0.0135	0.000145	0.045	0.0036	0.40	0.0052	0.028	0.0026	2.66	0.070	0.0010	0.00021	0.0094	0.000211	0.0017	0.00004	0.06	0.05
HN11	0.0045	0.0070	0.036	0.114	0.0584	0.000671	0.128	0.0071	0.98	0.0145	0.017	0.0017	3.92	0.091	0.0068	0.00159	0.0282	0.000663	0.0063	0.00013	0.06	0.09
PT1	0.0059	0.0137	0.012	0.049	0.0013	0.000018	0.090	0.0124	0.19	0.0060	0.076	0.0238	2.94	0.105	0.0018	0.00040	0.0009	0.000026	0.0458	0.00248	0.10	0.21
PT3	0.0071	0.0082	0.019	0.040	0.0032	0.000033	0.011	0.0007	0.41	0.0082	0.077	0.0129	2.87	0.055	0.0022	0.00045	0.0085	0.000188	0.0410	0.00121	0.05	0.07
PT4	0.0104	0.0030	0.014	0.025	0.0950	0.000867	0.018	0.0012	0.51	0.0094	0.020	0.0031	2.36	0.028	0.0010	0.00024	0.0997	0.001949	0.0119	0.00037	0.13	0.09
PT6	0.0101	0.0164	0.002	0.004	0.6023	0.009951	0.129	0.0112	0.40	0.0031	0.299	0.0634	3.06	0.052	0.0263	0.01358	0.2948	0.008982	0.1814	0.00806	0.09	0.04
PT7	0.0009	0.0015	0.003	0.014	0.0229	0.000297	0.324	0.0410	0.35	0.0028	0.577	0.1563	4.03	0.099	0.0011	0.00068	0.0153	0.000415	0.0059	0.00031	0.34	0.14
PT8	0.0064	0.0052	0.005	0.010	0.0220	0.000280	0.031	0.0021	0.33	0.0058	0.049	0.0079	0.40	0.007	0.0014	0.00041	0.0152	0.000400	0.0043	0.00013	0.07	0.08
PT9	0.0040	0.0028	0.002	0.003	0.0043	0.000053	0.014	0.0010	0.48	0.0082	0.019	0.0029	0.99	0.016	0.0012	0.00035	0.0145	0.000367	0.0065	0.00019	0.07	0.09
PT10	0.0036	0.0049	0.000	0.001	0.0252	0.000258	0.165	0.0079	0.14	0.0015	0.218	0.0194	2.55	0.049	0.0023	0.00054	0.0183	0.000389	0.0054	0.00010	0.09	0.07
PT11	0.0060	0.0093	0.037	0.075	0.0101	0.000097	0.036	0.0023	0.62	0.0101	0.035	0.0035	1.96	0.053	0.0041	0.00111	0.0142	0.000315	0.0070	0.00020	0.05	0.05
MK1	0.0005	0.0011	0.001	0.001	0.0055	0.000075	0.016	0.0012	0.08	0.0005	0.033	0.0031	1.30	0.042	0.0099	0.00254	0.0164	0.000446	0.0323	0.00071	0.11	0.14
MK2	0.0002	0.0005	0.151	0.449	0.0166	0.000195	0.016	0.0012	0.03	0.0002	0.055	0.0039	0.94	0.025	0.0036	0.00087	0.0260	0.000600	0.0025	0.00004	0.06	0.08
MK3	0.0001	0.0003	0.023	0.063	0.0137	0.000160	0.027	0.0017	0.09	0.0005	0.028	0.0027	1.35	0.041	0.0023	0.00050	0.0075	0.000176	0.0152	0.00033	0.07	0.11
MK4	0.0002	0.0007	0.026	0.078	0.0062	0.000083	0.032	0.0023	0.10	0.0007	0.038	0.0047	2.33	0.088	0.0089	0.00184	0.0029	0.000079	0.0055	0.00015	0.19	0.34
MK5	0.0003	0.0007	0.009	0.028	0.0026	0.000030	0.011	0.0006	0.06	0.0004	0.026	0.0025	1.57	0.052	0.0022	0.00046	0.0156	0.000380	0.0079	0.00017	0.20	0.26
MK6	0.0003	0.0008	0.016	0.055	0.0430	0.000581	0.023	0.0016	0.04	0.0003	0.037	0.0046	3.85	0.152	0.0038	0.00076	0.0119	0.000323	0.0023	0.00006	0.28	0.46
MK7	0.0054	0.0151	0.006	0.018	0.0180	0.000236	0.031	0.0023	0.40	0.0027	0.019	0.0020	1.04	0.031	0.0028	0.00060	0.0098	0.000259	0.0070	0.00016	0.20	0.30
MK8	0.0003	0.0007	0.045	0.118	0.0239	0.000282	0.056	0.0028	0.50	0.0060	0.016	0.0018	2.60	0.090	0.0114	0.00253	0.0202	0.000516	0.0249	0.00060	0.15	0.18
MK9	0.0002	0.0004	0.000	0.001	0.0049	0.000060	0.026	0.0017	0.34	0.0039	0.037	0.0029	2.37	0.070	0.0009	0.00022	0.0163	0.000401	0.0151	0.00028	0.03	0.04
MK10	0.0005	0.0010	0.006	0.017	0.0233	0.000280	0.027	0.0018	0.45	0.0051	0.017	0.0012	0.89	0.025	0.0006	0.00016	0.0121	0.000291	0.0498	0.00086	0.21	0.27
MK11	0.0008	0.0027	0.034	0.131	0.0298	0.000433	0.041	0.0034	0.11	0.0018	0.031	0.0044	0.67	0.028	0.0050	0.00111	0.0158	0.000466	0.0219	0.00062	0.13	0.27
MK12	0.0008	0.0020	0.002	0.005	0.0091	0.000112	0.054	0.0035	0.64	0.0083	0.035	0.0039	0.93	0.033	0.0066	0.00151	0.0056	0.000142	0.0124	0.00030	0.25	0.35
MK13	0.0001	0.0002	0.008	0.024	0.0128	0.000149	0.051	0.0031	0.36	0.0039	0.052	0.0046	2.14	0.065	0.0007	0.00016	0.0062	0.000145	0.0212	0.00044	0.15	0.22
MK14	0.0006	0.0016	0.005	0.018	0.0029	0.000041	0.032	0.0026	0.19	0.0027	0.011	0.0013	2.13	0.073	0.0014	0.00028	0.0009	0.000026	0.0021	0.00005	0.24	0.48

Table A3.4 *(cont.)* Physiological element concentrations (Con) in husk (mg kg^{-1}) and their transfer factors (TF) (n = 101)

Site	Bi		Cd		Ce		Co		Cr		Cs		Cu		Hf		La		Li		Mo	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
MK15	0.0007	0.0021	0.020	0.069	0.0290	0.000387	0.059	0.0041	0.09	0.0010	0.028	0.0035	1.95	0.076	0.0030	0.00063	0.0151	0.000409	0.0282	0.00073	0.28	0.47
MK16	0.0003	0.0010	0.015	0.053	0.0042	0.000054	0.039	0.0027	0.03	0.0005	0.084	0.0103	1.62	0.059	0.0043	0.00108	0.0032	0.000083	0.0030	0.00008	0.35	0.68
MK17	0.0010	0.0027	0.033	0.120	0.0551	0.000746	0.044	0.0031	0.03	0.0005	0.057	0.0068	1.20	0.044	0.0055	0.00138	0.0266	0.000731	0.0113	0.00029	0.11	0.16
MK18	0.0005	0.0011	0.022	0.067	0.0053	0.000061	0.031	0.0020	0.47	0.0060	0.020	0.0017	1.05	0.030	0.0003	0.00008	0.0030	0.000070	0.0526	0.00106	0.20	0.24
MK19	0.0015	0.0039	0.002	0.004	0.0020	0.000026	0.016	0.0011	0.07	0.0010	0.036	0.0043	1.24	0.044	0.0025	0.00060	0.0031	0.000081	0.0625	0.00163	0.45	0.78
MK20	0.0003	0.0008	0.009	0.028	0.0148	0.000182	0.045	0.0027	0.10	0.0011	0.017	0.0018	1.74	0.058	0.0015	0.00036	0.0078	0.000198	0.0222	0.00051	0.36	0.17
MK21	0.0007	0.0018	0.036	0.118	0.0245	0.000323	0.045	0.0037	0.06	0.0009	0.043	0.0045	0.62	0.021	0.0033	0.00079	0.0152	0.000404	0.0028	0.00007	0.20	0.26
MK22	0.0023	0.0056	0.001	0.005	0.0007	0.000008	0.053	0.0042	0.03	0.0004	0.029	0.0024	3.96	0.128	0.0002	0.00005	0.0001	0.000003	0.0049	0.00009	0.15	0.15
MK23	0.0005	0.0013	0.033	0.104	0.0007	0.000010	0.016	0.0012	0.08	0.0011	0.052	0.0042	1.40	0.042	0.0004	0.00011	0.0101	0.000272	0.0433	0.00082	0.26	0.24
MK24	0.0006	0.0016	0.036	0.102	0.0063	0.000079	0.030	0.0022	0.07	0.0010	0.062	0.0048	2.15	0.063	0.0015	0.00040	0.0286	0.000719	0.0622	0.00117	0.41	0.42
MK25	0.0003	0.0007	0.351	1.364	0.0139	0.000188	0.083	0.0070	0.09	0.0014	0.036	0.0035	1.84	0.066	0.0007	0.00017	0.0073	0.000198	0.0594	0.00133	0.36	0.54
MK26	0.0005	0.0012	0.012	0.071	0.0086	0.000109	0.029	0.0021	0.06	0.0006	0.024	0.0020	2.65	0.097	0.0030	0.00083	0.0012	0.000030	0.0742	0.00118	0.06	0.05
MK27	0.0003	0.0007	0.027	0.145	0.0119	0.000147	0.063	0.0045	0.02	0.0003	0.012	0.0013	1.71	0.085	0.0018	0.00040	0.0107	0.000269	0.0199	0.00037	0.28	0.28
MK30	0.0005	0.0012	0.007	0.029	0.0285	0.000356	0.041	0.0030	0.01	0.0001	0.056	0.0044	1.90	0.064	0.0012	0.00031	0.0147	0.000365	0.0016	0.00003	0.11	0.13
MK31	0.0009	0.0020	0.012	0.039	0.0069	0.000085	0.051	0.0033	0.09	0.0011	0.014	0.0012	4.62	0.141	0.0003	0.00007	0.0056	0.000139	0.0404	0.00087	0.22	0.29
MK32	0.0005	0.0011	0.005	0.017	0.0247	0.000288	0.031	0.0022	0.23	0.0030	0.038	0.0034	1.85	0.057	0.0022	0.00054	0.0150	0.000354	0.0009	0.00002	0.22	0.35
MK33	0.0008	0.0017	0.018	0.063	0.0685	0.000794	0.048	0.0037	0.02	0.0002	0.042	0.0035	1.38	0.041	0.0089	0.00224	0.0362	0.000829	0.0235	0.00047	0.06	0.08
MK34	0.0003	0.0009	0.030	0.125	0.0322	0.000411	0.032	0.0024	0.02	0.0003	0.022	0.0021	2.19	0.071	0.0021	0.00050	0.0160	0.000402	0.0004	0.00001	0.06	0.08
MK35	0.0005	0.0013	0.024	0.100	0.0419	0.000496	0.021	0.0015	0.09	0.0011	0.014	0.0012	6.22	0.215	0.0027	0.00063	0.0386	0.000905	0.0107	0.00022	0.27	0.44
MK36	0.0028	0.0065	0.009	0.035	0.0147	0.000136	0.019	0.0013	0.04	0.0005	0.045	0.0035	1.48	0.043	0.0008	0.00021	0.0390	0.000739	0.0074	0.00012	0.07	0.07
MK37	0.0013	0.0035	0.009	0.031	0.0955	0.001186	0.045	0.0032	0.05	0.0006	0.035	0.0036	0.57	0.019	0.0037	0.00084	0.0480	0.001199	0.0318	0.00074	0.18	0.29
MK38	0.0004	0.0010	0.006	0.028	0.0104	0.000137	0.021	0.0016	0.01	0.0001	0.019	0.0015	2.16	0.074	0.0029	0.00076	0.0040	0.000103	0.0468	0.00089	0.15	0.18
MK40	0.0005	0.0012	0.014	0.044	0.0350	0.000441	0.044	0.0032	0.01	0.0001	0.025	0.0019	0.95	0.027	0.0016	0.00041	0.0123	0.000302	0.0104	0.00019	0.28	0.33
MK41	0.0005	0.0010	0.003	0.007	0.0085	0.000103	0.071	0.0048	0.02	0.0002	0.011	0.0009	1.36	0.039	0.0068	0.00180	0.0065	0.000155	0.0095	0.00018	0.16	0.19
MK42	0.0011	0.0025	0.051	0.138	0.1325	0.001721	0.089	0.0066	0.06	0.0006	0.027	0.0026	2.62	0.083	0.0070	0.00169	0.0702	0.001797	0.0326	0.00075	0.16	0.17
MK43	0.0002	0.0006	0.061	0.347	0.0105	0.000139	0.081	0.0093	0.13	0.0023	0.083	0.0098	0.83	0.035	0.0099	0.00223	0.0054	0.000143	0.0152	0.00035	0.07	0.07
MK44	0.0011	0.0026	0.021	0.131	0.0234	0.000284	0.026	0.0029	0.05	0.0006	0.088	0.0068	1.64	0.060	0.0018	0.00044	0.0120	0.000284	0.0025	0.00004	0.31	0.31
MK45	0.0003	0.0008	0.092	0.416	0.0097	0.000111	0.013	0.0012	0.03	0.0004	0.033	0.0031	0.64	0.024	0.0143	0.00333	0.0093	0.000214	0.0226	0.00044	0.01	0.01
MK46	0.0004	0.0012	0.001	0.005	0.0146	0.000198	0.001	0.0001	0.03	0.0005	0.034	0.0033	1.72	0.070	0.0057	0.00132	0.0387	0.001023	0.0151	0.00030	0.08	0.06
MK47	0.0001	0.0002	0.032	0.150	0.0067	0.000088	0.002	0.0002	0.07	0.0009	0.063	0.0058	0.79	0.032	0.0024	0.00056	0.0023	0.000059	0.0236	0.00046	0.03	0.02
MK48	0.0007	0.0018	0.061	0.387	0.0188	0.000259	0.085	0.0150	0.10	0.0017	0.136	0.0133	2.88	0.101	0.0018	0.00043	0.0092	0.000248	0.0410	0.00088	0.03	0.02
MK49	0.0006	0.0015	0.064	0.411	0.0157	0.000201	0.041	0.0054	0.04	0.0006	0.030	0.0024	1.25	0.046	0.0015	0.00041	0.0079	0.000200	0.0064	0.00011	0.19	0.15
MK51	0.0001	0.0005	0.003	0.012	0.0279	0.000400	0.006	0.0005	0.19	0.0032	0.038	0.0048	2.18	0.089	0.0005	0.00014	0.0133	0.000385	0.0086	0.00024	0.08	0.13
MK52	0.0002	0.0004	0.021	0.071	0.0055	0.000068	0.137	0.0067	0.01	0.0002	0.005	0.0004	1.45	0.042	0.0001	0.00004	0.0025	0.000059	0.0131	0.00026	0.06	0.05
MK53	0.0004	0.0008	0.039	0.134	0.0001	0.000002	0.049	0.0036	0.10	0.0011	0.011	0.0009	0.59	0.017	0.0048	0.00125	0.0294	0.000718	0.0168	0.00033	0.01	0.01
MK54	0.0001	0.0002	0.022	0.072	0.0166	0.000200	0.058	0.0042	0.01	0.0001	0.066	0.0054	0.47	0.013	0.0026	0.00067	0.0990	0.002360	0.0393	0.00077	0.06	0.07
MK55	0.0007	0.0015	0.003	0.008	0.0086	0.000093	0.039	0.0023	0.04	0.0005	0.018	0.0014	2.05	0.053	0.0041	0.00116	0.0014	0.000030	0.0126	0.00022	0.03	0.03

Table A3.4 *(cont.)* Physiological element concentrations (Con) in husk (mg kg^{-1}) and their transfer factors (TF) (n = 101)

Site	Bi		Cd		Ce		Co		Cr		Cs		Cu		Hf		La		Li		Mo	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
MK56	0.0002	0.0004	0.029	0.087	0.0674	0.000709	0.021	0.0012	0.17	0.0019	0.012	0.0008	1.41	0.034	0.0003	0.00007	0.0221	0.000468	0.0182	0.00030	0.12	0.10
MK57	0.0003	0.0006	0.025	0.077	0.0025	0.000028	0.024	0.0014	0.35	0.0045	0.014	0.0013	1.47	0.046	0.0041	0.00110	0.0072	0.000161	0.0211	0.00046	0.06	0.06
MK58	0.0002	0.0004	0.009	0.035	0.0071	0.000078	0.028	0.0018	0.03	0.0004	0.013	0.0011	1.33	0.039	0.0008	0.00023	0.0043	0.000094	0.0116	0.00024	0.07	0.07
MK59	0.0002	0.0006	0.001	0.003	0.0045	0.000066	0.024	0.0019	0.83	0.0120	0.015	0.0015	1.62	0.057	0.0035	0.00112	0.0236	0.000677	0.0161	0.00038	0.07	0.10
MK60	0.0003	0.0007	0.019	0.065	0.0169	0.000221	0.007	0.0005	0.07	0.0009	0.011	0.0010	0.87	0.027	0.0048	0.00138	0.0081	0.000210	0.0081	0.00018	0.05	0.07
MK61	0.0002	0.0005	0.035	0.114	0.0130	0.000166	0.038	0.0027	0.09	0.0012	0.025	0.0028	1.69	0.058	0.0048	0.00118	0.0082	0.000212	0.0384	0.00102	0.18	0.29
MK62	0.0006	0.0017	0.052	0.184	0.0368	0.000494	0.013	0.0010	0.39	0.0063	0.029	0.0030	1.28	0.050	0.0007	0.00014	0.0178	0.000471	0.0080	0.00019	0.08	0.13
MK63	0.0007	0.0018	0.000	0.001	0.0468	0.000597	0.007	0.0004	0.17	0.0025	0.087	0.0090	3.17	0.110	0.0012	0.00028	0.0240	0.000618	0.0109	0.00026	0.33	0.49
MK64	0.0004	0.0009	0.031	0.137	0.3281	0.004134	0.064	0.0059	0.03	0.0003	0.055	0.0042	3.21	0.110	0.0050	0.00111	0.1426	0.003453	0.1363	0.00237	0.02	0.02
MK65	0.0021	0.0051	0.001	0.002	0.0030	0.000030	0.040	0.0020	0.84	0.0098	0.029	0.0020	1.50	0.053	0.0013	0.00033	0.0222	0.000433	0.0404	0.00059	0.08	0.09
MK66	0.0003	0.0007	0.167	0.565	0.0103	0.000114	0.070	0.0037	0.27	0.0031	0.025	0.0018	6.47	0.197	0.0103	0.00242	0.0067	0.000146	0.0154	0.00024	0.46	0.53
MK67	0.0036	0.0087	0.016	0.094	0.0457	0.000546	0.120	0.0132	0.02	0.0001	0.025	0.0019	6.58	0.247	0.0206	0.00466	0.0339	0.000798	0.0148	0.00025	0.09	0.09
MK68	0.0004	0.0010	0.028	0.140	0.0303	0.000353	0.082	0.0094	0.62	0.0041	0.019	0.0014	2.27	0.082	0.0031	0.00071	0.0320	0.000732	0.0800	0.00136	0.11	0.11
MK69	0.0004	0.0010	0.060	0.339	0.0180	0.000213	0.041	0.0046	0.47	0.0033	0.019	0.0014	3.45	0.129	0.0020	0.00047	0.0490	0.001124	0.0688	0.00113	0.12	0.13
MK70	0.0004	0.0008	0.001	0.005	0.0002	0.000002	0.122	0.0117	0.12	0.0007	0.217	0.0157	1.89	0.068	0.0029	0.00069	0.0002	0.000005	0.0077	0.00012	1.22	1.29
MK71	0.0009	0.0020	0.003	0.018	0.0359	0.000429	0.070	0.0069	1.29	0.0077	0.050	0.0038	1.88	0.068	0.0016	0.00038	0.0034	0.000079	0.0404	0.00066	0.03	0.04
MK72	0.0004	0.0011	0.026	0.125	0.0006	0.000008	0.047	0.0057	0.10	0.0007	0.082	0.0088	2.86	0.100	0.0019	0.00037	0.0004	0.000011	0.0456	0.00105	0.04	0.02
MK73	0.0001	0.0004	0.014	0.070	0.0266	0.000353	0.029	0.0028	0.11	0.0007	0.058	0.0057	0.91	0.036	0.0077	0.00157	0.0231	0.000607	0.0161	0.00034	0.03	0.02
MK74	0.0003	0.0008	0.033	0.164	0.0146	0.000210	0.050	0.0063	0.02	0.0002	0.075	0.0081	2.46	0.094	0.0094	0.00183	0.0075	0.000213	0.0330	0.00077	0.30	0.20
MK75	0.0001	0.0004	0.021	0.099	0.0133	0.000166	0.083	0.0078	0.07	0.0006	0.021	0.0024	2.00	0.088	0.0696	0.01437	0.0075	0.000186	0.0400	0.00093	0.15	0.20
MK76	0.0002	0.0004	0.003	0.011	0.0018	0.000020	0.053	0.0050	0.05	0.0003	0.042	0.0029	0.83	0.023	0.0003	0.00006	0.0025	0.000056	0.0020	0.00003	0.20	0.12
MK77	0.0004	0.0010	0.026	0.072	0.0022	0.000028	0.075	0.0049	0.05	0.0006	0.063	0.0056	1.17	0.035	0.0002	0.00006	0.0012	0.000030	0.0100	0.00020	0.26	0.29
MK78	0.0008	0.0020	0.019	0.075	0.0064	0.000078	0.064	0.0047	0.15	0.0018	0.021	0.0016	1.26	0.039	0.0040	0.00101	0.0075	0.000179	0.0010	0.00002	0.21	0.18
MK79	0.0002	0.0005	0.028	0.088	0.0061	0.000066	0.083	0.0056	0.19	0.0021	0.070	0.0048	5.41	0.126	0.0037	0.00100	0.0094	0.000206	0.0098	0.00014	0.44	0.17
MK80	0.0002	0.0005	0.013	0.060	0.0067	0.000079	0.092	0.0081	0.40	0.0054	0.014	0.0011	1.81	0.061	0.0008	0.00021	0.0038	0.000088	0.0064	0.00011	0.10	0.08
MK81	0.0004	0.0010	0.007	0.023	0.0037	0.000039	0.044	0.0029	0.14	0.0017	0.036	0.0029	2.09	0.072	0.0006	0.00014	0.0032	0.000069	0.0456	0.00078	0.07	0.05
MK82	0.0002	0.0006	0.008	0.038	0.0004	0.000005	0.082	0.0098	0.28	0.0041	0.063	0.0056	3.39	0.152	0.0021	0.00049	0.0041	0.000092	0.0276	0.00047	0.11	0.09

Table A3.4 *(cont.)* Physiological element concentrations (Con) in husk (mg kg^{-1}) and their transfer factors (TF) (n = 101)

Site	Ni		Pb		Rb		Sb		Sn		Sr		Th		Tl		U		Zn		Zr	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
H1	0.48	0.013	1.59	0.042	24.0	0.180	0.0146	0.00824	<0.06	<0.01	2.25	0.06	0.0003	0.00001	0.0006	0.0009	0.0081	0.00156	10.0	0.09	0.044	0.0005
H5	0.36	0.012	0.65	0.021	47.8	0.390	0.0207	0.01207	<0.06	<0.01	7.58	0.18	0.0007	0.00003	0.0065	0.0103	0.0019	0.00041	9.3	0.11	0.014	0.0001
H6	0.59	0.027	0.40	0.018	66.9	0.686	0.0011	0.00083	<0.06	<0.02	4.60	0.11	0.0010	0.00006	0.0039	0.0080	0.0009	0.00023	8.6	0.13	0.032	0.0003
H7	0.35	0.014	0.31	0.013	57.9	0.551	0.0015	0.00100	<0.06	<0.01	6.17	0.16	0.0012	0.00007	0.0008	0.0015	0.0021	0.00053	10.2	0.15	0.104	0.0010
HN1	0.41	0.009	1.67	0.048	4.3	0.034	0.0491	0.02607	<0.06	<0.01	4.46	0.05	0.0043	0.00025	0.0057	0.0092	0.0060	0.00160	12.9	0.13	0.167	0.0011
HN2	0.32	0.009	0.49	0.016	15.3	0.142	0.0194	0.01213	<0.06	<0.01	3.01	0.04	0.0491	0.00311	0.0037	0.0070	0.0027	0.00080	6.3	0.07	0.279	0.0018
HN3	0.13	0.004	0.90	0.027	11.0	0.099	0.0221	0.01365	<0.06	<0.01	3.25	0.04	0.0072	0.00051	0.0040	0.0073	0.0015	0.00048	6.3	0.06	0.150	0.0011
HN5	0.17	0.004	0.38	0.011	12.1	0.105	0.0240	0.01294	<0.06	<0.01	3.32	0.05	0.0085	0.00056	0.0033	0.0057	0.0063	0.00178	2.0	0.02	0.071	0.0005
HN6	0.82	0.018	0.41	0.011	12.6	0.098	0.0129	0.00635	<0.06	<0.01	6.04	0.08	0.0072	0.00043	0.0042	0.0068	0.0085	0.00232	22.4	0.23	0.069	0.0005
HN7	0.22	0.005	0.24	0.006	11.2	0.078	0.0065	0.00343	<0.06	<0.01	2.53	0.03	0.0022	0.00012	0.0028	0.0040	0.0025	0.00066	6.6	0.06	0.078	0.0005
HN8	0.34	0.007	0.24	0.006	14.8	0.105	0.0079	0.00405	<0.06	<0.01	2.96	0.04	0.0008	0.00004	0.0027	0.0038	0.0010	0.00027	10.3	0.10	0.164	0.0011
HN9	1.21	0.024	0.37	0.008	5.2	0.037	0.0145	0.00697	5.18	1.163	2.56	0.03	0.0027	0.00015	0.0028	0.0039	0.0034	0.00084	12.3	0.11	0.041	0.0003
HN10	0.85	0.025	0.73	0.019	12.8	0.095	0.0170	0.00488	1.58	0.331	5.71	0.07	0.0016	0.00009	0.0021	0.0030	0.0026	0.00063	16.4	0.18	0.078	0.0005
HN11	1.01	0.022	2.93	0.069	8.6	0.060	0.0099	0.00524	0.52	0.100	2.98	0.04	0.0264	0.00159	0.0036	0.0052	0.0139	0.00379	6.2	0.05	0.321	0.0023
PT1	0.31	0.017	2.53	0.064	31.6	0.491	0.0968	0.09336	<0.06	<0.01	4.48	0.06	0.0147	0.00111	0.0043	0.0133	0.0124	0.00433	17.9	0.26	0.162	0.0011
PT3	0.23	0.006	0.35	0.005	40.5	0.382	0.0127	0.00721	<0.06	<0.01	4.47	0.05	0.0085	0.00051	0.0049	0.0092	0.0011	0.00031	10.1	0.10	0.018	0.0001
PT4	0.21	0.005	0.65	0.008	6.9	0.059	0.0121	0.00440	<0.06	<0.01	2.25	0.02	0.0268	0.00165	0.0058	0.0103	0.0022	0.00060	11.1	0.08	0.084	0.0007
PT6	0.51	0.019	2.27	0.041	28.0	0.432	0.0640	0.04738	<0.06	<0.01	6.61	0.19	0.1011	0.00416	0.0075	0.0199	0.0298	0.00782	7.4	0.05	0.981	0.0162
PT7	1.59	0.070	0.64	0.013	30.9	0.635	0.0005	0.00045	<0.06	<0.01	4.47	0.15	0.0016	0.00005	0.0010	0.0033	0.0112	0.00265	40.5	0.49	0.065	0.0014
PT8	0.15	0.004	0.48	0.006	25.4	0.245	0.0160	0.00721	<0.06	<0.01	4.18	0.04	0.0012	0.00008	0.0041	0.0076	0.0029	0.00088	1.7	0.01	0.085	0.0008
PT9	0.15	0.004	0.40	0.005	11.8	0.109	0.0095	0.00452	<0.06	<0.01	3.55	0.03	0.0003	0.00002	0.0037	0.0069	0.0006	0.00019	2.1	0.02	0.018	0.0002
PT10	2.04	0.037	0.73	0.015	7.1	0.047	0.0354	0.02059	2.11	0.400	4.40	0.06	0.0013	0.00007	0.0039	0.0049	0.0052	0.00124	10.6	0.07	0.122	0.0009
PT11	0.35	0.009	0.72	0.014	11.7	0.088	0.0138	0.00487	2.85	0.423	4.13	0.10	0.0011	0.00006	0.0036	0.0051	0.0042	0.00100	14.9	0.12	0.172	0.0015
MK1	0.08	0.002	0.84	0.033	17.9	0.150	0.0111	0.00572	<0.06	<0.01	1.30	0.01	0.0008	0.00006	0.0005	0.0008	0.0005	0.00013	9.4	0.09	0.350	0.0024
MK2	0.10	0.002	0.27	0.009	23.4	0.164	0.0143	0.00613	<0.06	<0.01	3.12	0.04	0.0010	0.00006	0.0005	0.0006	0.0001	0.00003	9.1	0.09	0.117	0.0008
MK3	0.15	0.004	0.27	0.009	13.6	0.113	0.0012	0.00044	<0.06	<0.01	2.83	0.03	0.0089	0.00054	0.0001	0.0002	0.0012	0.00026	9.7	0.10	0.070	0.0004
MK4	0.49	0.016	0.76	0.031	15.8	0.154	0.0002	0.00008	<0.06	<0.01	2.02	0.02	0.0052	0.00036	0.0001	0.0003	0.0018	0.00047	72.0	0.98	0.306	0.0018
MK5	1.57	0.041	0.51	0.018	16.4	0.133	0.0017	0.00070	0.21	0.048	2.11	0.02	0.0057	0.00035	0.0002	0.0003	0.0005	0.00011	14.9	0.15	0.071	0.0004
MK6	0.19	0.006	0.69	0.030	15.4	0.156	0.0018	0.00092	<0.06	<0.01	2.81	0.03	0.0068	0.00047	0.0003	0.0006	0.0002	0.00007	1.0	0.01	0.116	0.0006
MK7	0.23	0.007	0.40	0.016	12.5	0.115	0.0031	0.00153	0.28	0.075	3.44	0.04	0.0043	0.00029	0.0004	0.0006	0.0003	0.00006	13.2	0.14	0.103	0.0006
MK8	0.59	0.017	0.68	0.023	8.3	0.075	0.0099	0.00483	0.19	0.048	3.34	0.04	0.0064	0.00045	0.0002	0.0004	0.0015	0.00033	11.2	0.13	0.446	0.0027
MK9	0.14	0.003	0.51	0.018	2.8	0.020	0.0040	0.00192	0.26	0.056	1.99	0.02	0.0065	0.00041	0.0002	0.0002	0.0002	0.00004	1.5	0.02	0.092	0.0006
MK10	0.25	0.006	0.73	0.023	6.6	0.045	0.0019	0.00075	<0.06	<0.01	2.01	0.02	0.0018	0.00010	0.0095	0.0115	0.0018	0.00036	16.0	0.14	0.039	0.0003
MK11	0.10	0.004	0.36	0.016	10.8	0.115	0.0061	0.00317	0.80	0.232	2.61	0.03	0.0035	0.00027	0.0002	0.0005	0.0031	0.00080	10.3	0.14	0.045	0.0003
MK12	0.40	0.012	0.34	0.014	14.6	0.129	0.0023	0.00098	0.88	0.209	2.90	0.04	0.0006	0.00004	0.0008	0.0013	0.0007	0.00018	14.0	0.18	0.091	0.0006
MK13	0.89	0.023	0.60	0.020	23.7	0.181	0.0009	0.00038	<0.06	<0.01	2.88	0.03	0.0006	0.00004	0.0007	0.0010	0.0025	0.00050	11.4	0.11	0.034	0.0002
MK14	0.19	0.006	0.79	0.004	7.8	0.072	0.0005	0.00007	2.74	0.630	2.53	0.03	0.0001	0.00001	0.0014	0.0026	0.0002	0.00005	10.0	0.12	0.105	0.0006

Table A3.4 *(cont.)* Physiological element concentrations (Con) in husk (mg kg^{-1}) and their transfer factors (TF) (n = 101)

Site	Ni		Pb		Rb		Sb		Sn		Sr		Th		Tl		U		Zn		Zr	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
MK15	0.14	0.005	0.29	0.012	7.5	0.074	0.0025	0.00121	<0.06	<0.01	2.80	0.03	0.0075	0.00052	0.0002	0.0003	0.0016	0.00039	20.3	0.28	0.136	0.0008
MK16	0.16	0.005	0.34	0.014	16.4	0.157	0.0027	0.00124	<0.06	<0.01	3.98	0.04	0.0014	0.00010	0.0021	0.0038	0.0005	0.00011	13.4	0.18	0.052	0.0004
MK17	0.22	0.007	0.37	0.015	23.4	0.228	0.0004	0.00020	<0.06	<0.01	2.78	0.03	0.0110	0.00077	0.0010	0.0018	0.0038	0.00092	13.9	0.18	0.173	0.0012
MK18	0.15	0.004	0.36	0.012	7.6	0.056	0.0002	0.00009	<0.06	<0.01	1.80	0.02	0.0004	0.00002	0.0002	0.0003	0.0004	0.00008	10.5	0.10	0.014	0.0001
MK19	0.36	0.011	0.02	0.001	19.9	0.187	0.0090	0.00372	<0.06	<0.01	4.34	0.05	0.0096	0.00065	0.0010	0.0017	0.0017	0.00038	17.3	0.21	0.084	0.0006
MK20	0.15	0.004	0.66	0.025	5.6	0.048	0.0008	0.00038	<0.06	<0.01	3.07	0.04	0.0012	0.00008	0.0004	0.0006	0.0010	0.00023	24.7	0.28	0.017	0.0001
MK21	0.05	0.001	0.69	0.028	21.5	0.198	0.0041	0.00198	0.16	0.042	3.86	0.05	0.0014	0.00010	0.0001	0.0002	0.0016	0.00037	24.0	0.28	0.114	0.0008
MK22	0.38	0.010	0.49	0.019	18.8	0.152	0.0003	0.00015	<0.06	<0.01	3.62	0.05	0.0068	0.00043	0.0033	0.0045	0.0010	0.00019	29.1	0.32	0.302	0.0020
MK23	0.20	0.005	0.40	0.015	24.4	0.220	0.0002	0.00008	<0.06	<0.01	4.03	0.05	0.0083	0.00056	0.0044	0.0062	0.0002	0.00004	15.5	0.16	0.080	0.0006
MK24	0.19	0.005	0.35	0.013	19.8	0.163	0.0005	0.00024	<0.06	<0.01	3.57	0.04	0.0005	0.00003	0.0005	0.0007	0.0020	0.00040	25.6	0.26	0.094	0.0007
MK25	0.13	0.004	0.34	0.014	13.5	0.125	0.0035	0.00176	<0.06	<0.01	3.41	0.04	0.0003	0.00002	0.0015	0.0024	0.0017	0.00039	19.3	0.21	0.035	0.0002
MK26	0.41	0.010	0.24	0.009	10.8	0.080	0.0007	0.00056	<0.06	<0.01	4.72	0.06	0.0019	0.00011	0.0006	0.0009	0.0026	0.00056	20.3	0.21	0.012	0.0001
MK27	0.11	0.003	0.21	0.009	6.7	0.058	0.0011	0.00105	<0.06	<0.01	5.55	0.07	0.0024	0.00016	0.0006	0.0011	0.0005	0.00010	12.1	0.15	0.103	0.0006
MK30	0.13	0.003	0.17	0.006	17.6	0.131	0.0245	0.01104	<0.06	<0.01	4.02	0.05	0.0064	0.00040	0.0002	0.0002	0.0041	0.00091	10.8	0.11	0.060	0.0004
MK31	0.21	0.006	0.26	0.009	6.5	0.051	0.0025	0.00105	<0.06	<0.01	3.34	0.04	0.0002	0.00001	0.0008	0.0012	0.0022	0.00051	44.8	0.46	0.021	0.0001
MK32	0.16	0.004	0.13	0.004	11.8	0.091	0.0008	0.00033	<0.06	<0.01	4.03	0.05	0.0031	0.00020	0.0014	0.0020	0.0027	0.00054	11.8	0.12	0.077	0.0005
MK33	0.09	0.002	0.10	0.003	12.2	0.092	0.0078	0.00348	<0.06	<0.01	4.70	0.06	0.0015	0.00009	0.0008	0.0011	0.0138	0.00288	17.7	0.17	0.257	0.0018
MK34	0.42	0.012	0.38	0.015	7.7	0.063	0.0055	0.00285	<0.06	<0.01	3.13	0.04	0.0059	0.00039	0.0077	0.0120	0.0008	0.00019	14.2	0.16	0.068	0.0005
MK35	0.24	0.006	0.11	0.004	6.3	0.050	0.0006	0.00031	<0.06	<0.01	3.08	0.04	0.0061	0.00039	0.0017	0.0025	0.0020	0.00042	32.2	0.35	0.164	0.0010
MK36	0.04	0.001	0.06	0.002	14.5	0.113	0.0053	0.00248	<0.06	<0.01	3.66	0.05	0.0018	0.00011	0.0090	0.0125	0.0027	0.00052	8.5	0.07	0.048	0.0003
MK37	0.28	0.008	0.11	0.004	7.5	0.064	0.0011	0.00061	<0.06	<0.01	3.61	0.04	0.0207	0.00139	0.0003	0.0004	0.0076	0.00177	8.8	0.10	0.097	0.0006
MK38	0.04	0.001	0.30	0.012	2.9	0.022	0.0005	0.00026	<0.06	<0.01	2.05	0.02	0.0081	0.00053	0.0002	0.0002	0.0003	0.00007	14.6	0.16	0.098	0.0007
MK40	0.15	0.004	0.13	0.005	11.7	0.086	0.0037	0.00172	1.56	0.38	3.56	0.04	0.0093	0.00059	0.0007	0.0009	0.0075	0.00158	16.7	0.16	0.160	0.0011
MK41	0.10	0.002	0.25	0.008	6.8	0.050	0.0009	0.00035	1.65	0.37	2.39	0.03	0.0007	0.00004	0.0003	0.0004	0.0009	0.00019	8.9	0.08	0.106	0.0007
MK42	0.19	0.005	0.90	0.033	6.8	0.057	0.0016	0.00060	0.45	0.10	3.11	0.04	0.0145	0.00096	0.0002	0.0003	0.0068	0.00160	16.2	0.17	0.265	0.0017
MK43	0.48	0.019	0.51	0.024	21.5	0.211	0.0007	0.00048	3.45	1.02	3.94	0.05	0.0009	0.00006	0.0010	0.0018	0.0006	0.00016	14.7	0.24	0.508	0.0031
MK44	0.16	0.005	0.41	0.015	20.8	0.161	0.0011	0.00065	<0.06	<0.01	3.92	0.04	0.0020	0.00013	0.0005	0.0006	0.0225	0.00485	33.3	0.45	0.071	0.0005
MK45	0.14	0.005	0.28	0.011	15.7	0.137	0.0002	0.00011	1.57	0.38	4.38	0.05	0.0004	0.00003	0.0007	0.0011	0.0014	0.00028	14.2	0.18	0.592	0.0037
MK46	0.11	0.005	0.21	0.010	19.5	0.162	0.0009	0.00062	0.55	0.14	4.44	0.05	0.0024	0.00017	0.0003	0.0006	0.0002	0.00006	12.9	0.24	0.443	0.0028
MK47	0.16	0.005	0.27	0.011	18.5	0.153	0.0008	0.00047	0.47	0.12	3.39	0.04	0.0057	0.00037	0.0005	0.0008	0.0006	0.00014	15.2	0.21	0.090	0.0006
MK48	0.27	0.012	0.30	0.013	26.7	0.232	0.0016	0.00101	0.59	0.15	5.75	0.07	0.0010	0.00007	0.0004	0.0006	0.0006	0.00013	17.5	0.34	0.076	0.0005
MK49	0.20	0.007	0.43	0.016	14.6	0.113	0.0058	0.00354	<0.06	<0.01	2.18	0.03	0.0007	0.00004	0.0002	0.0003	0.0012	0.00027	13.7	0.20	0.051	0.0004
MK51	0.05	0.002	0.81	0.037	15.7	0.165	0.0028	0.00149	0.21	0.07	3.62	0.05	0.0037	0.00029	0.0011	0.0021	0.0018	0.00050	8.7	0.12	0.026	0.0002
MK52	0.28	0.006	0.37	0.014	6.6	0.049	0.0010	0.00041	<0.06	<0.01	2.01	0.02	0.0005	0.00003	0.0005	0.0007	0.0013	0.00029	15.9	0.15	0.013	0.0001
MK53	0.09	0.002	0.34	0.012	7.3	0.054	0.0006	0.00026	<0.06	<0.01	2.36	0.03	0.0177	0.00112	0.0001	0.0001	0.0001	0.00002	12.1	0.12	0.095	0.0007
MK54	0.31	0.008	0.36	0.012	30.0	0.224	0.0020	0.00085	0.48	0.11	3.54	0.04	0.0035	0.00022	0.0007	0.0010	0.0063	0.00145	12.0	0.11	0.097	0.0007
MK55	1.72	0.037	0.41	0.013	14.4	0.100	0.0001	0.00003	0.25	0.06	3.04	0.04	0.0067	0.00041	0.0007	0.0010	0.0013	0.00029	6.1	0.05	0.015	0.0001

Table A3.4 *(cont.)* Physiological element concentrations (Con) in husk (mg kg^{-1}) and their transfer factors (TF) (n = 101)

Site	Ni		Pb		Rb		Sb		Sn		Sr		Th		Tl		U		Zn		Zr	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
MK56	0.20	0.004	0.94	0.030	7.2	0.049	0.0017	0.00064	0.18	0.04	3.21	0.04	0.0017	0.00010	0.0001	0.0001	0.0015	0.00031	11.5	0.10	0.028	0.0002
MK57	0.25	0.006	0.53	0.020	7.6	0.063	0.0013	0.00062	<0.06	<0.01	3.80	0.05	0.0005	0.00003	0.0003	0.0005	0.0020	0.00045	10.5	0.10	0.130	0.0009
MK58	0.25	0.006	0.29	0.011	10.4	0.086	0.0010	0.00044	0.54	0.14	4.70	0.06	0.0022	0.00015	0.0009	0.0013	0.0014	0.00031	4.0	0.04	0.043	0.0003
MK59	0.34	0.010	0.69	0.029	6.5	0.056	0.0016	0.00090	0.28	0.08	2.76	0.03	0.0030	0.00023	0.0016	0.0025	0.0010	0.00029	12.7	0.15	0.143	0.0012
MK60	0.09	0.002	0.45	0.017	15.3	0.120	0.0002	0.00008	0.66	0.16	3.23	0.04	0.0035	0.00024	0.0001	0.0002	0.0008	0.00020	10.1	0.11	0.046	0.0004
MK61	0.35	0.011	0.44	0.017	20.7	0.188	0.0059	0.00268	0.78	0.20	3.21	0.04	0.0014	0.00010	0.0005	0.0008	0.0007	0.00016	21.4	0.26	0.024	0.0002
MK62	0.04	0.001	0.31	0.013	18.2	0.166	0.0006	0.00035	0.34	0.09	2.63	0.04	0.0038	0.00026	0.0004	0.0007	0.0011	0.00024	17.7	0.21	0.037	0.0002
MK63	1.10	0.032	0.66	0.025	15.2	0.134	0.0011	0.00057	0.98	0.24	4.18	0.05	0.0002	0.00002	0.0013	0.0022	0.0011	0.00025	3.0	0.03	0.030	0.0002
MK64	1.49	0.043	0.54	0.020	20.2	0.156	0.0013	0.00065	0.44	0.09	2.00	0.02	0.1152	0.00805	0.0030	0.0042	0.0344	0.00801	15.3	0.18	0.139	0.0008
MK65	1.52	0.032	0.32	0.012	16.1	0.113	0.0016	0.00083	0.08	0.02	3.07	0.04	0.0002	0.00001	0.0001	0.0001	0.0015	0.00031	13.9	0.10	0.014	0.0001
MK66	0.55	0.012	0.30	0.010	21.0	0.149	0.0007	0.00037	0.43	0.1	3.45	0.04	0.0050	0.00031	0.0004	0.0005	0.0039	0.00084	15.8	0.13	0.212	0.0013
MK67	0.23	0.007	0.21	0.008	0.6	0.004	0.0088	0.00618	0.29	0.07	4.80	0.06	0.0749	0.00452	0.0002	0.0002	0.0121	0.00279	20.8	0.27	0.702	0.0042
MK68	0.18	0.006	0.30	0.012	2.2	0.014	0.0006	0.00043	0.08	0.02	5.02	0.06	0.0013	0.00008	0.0021	0.0029	0.0008	0.00019	17.1	0.21	0.102	0.0006
MK69	0.45	0.014	0.23	0.009	3.2	0.021	0.0044	0.00304	0.08	0.02	3.27	0.04	0.0032	0.00019	0.0004	0.0005	0.0010	0.00022	16.8	0.22	0.011	0.0001
MK70	0.05	0.001	0.24	0.009	5.6	0.038	0.0023	0.00137	<0.06	<0.01	2.79	0.03	0.0017	0.00011	0.0003	0.0004	0.0014	0.00034	10.4	0.13	0.130	0.0008
MK71	1.86	0.054	0.33	0.012	5.9	0.041	0.0012	0.00071	0.13	0.03	3.16	0.03	0.0005	0.00003	0.0002	0.0003	0.0008	0.00021	12.1	0.15	0.089	0.0006
MK72	0.65	0.025	2.25	0.092	3.3	0.029	0.0043	0.00318	0.58	0.15	2.11	0.02	0.0035	0.00022	0.0002	0.0005	0.0027	0.00066	24.1	0.33	0.098	0.0005
MK73	0.08	0.003	0.43	0.018	6.3	0.053	0.0003	0.00025	<0.06	<0.01	2.54	0.03	0.0002	0.00001	0.0003	0.0005	0.0013	0.00033	16.5	0.23	0.030	0.0002
MK74	0.35	0.014	0.22	0.010	3.2	0.029	0.0069	0.00533	<0.06	<0.01	2.96	0.03	0.0014	0.00009	0.0005	0.0009	0.0005	0.00013	19.4	0.28	0.055	0.0003
MK75	0.49	0.018	0.68	0.027	8.8	0.082	0.0063	0.00454	<0.06	<0.01	3.75	0.05	0.0026	0.00017	0.0005	0.0009	0.0007	0.00016	16.6	0.25	0.107	0.0006
MK76	0.32	0.008	0.26	0.008	15.5	0.127	0.0004	0.00018	<0.06	<0.01	2.46	0.03	0.0172	0.00106	0.0002	0.0003	0.0013	0.00026	15.6	0.19	0.027	0.0002
MK77	6.48	0.170	0.54	0.021	60.9	0.522	0.0024	0.00122	<0.06	<0.01	1.45	0.02	0.0001	0.00001	0.0003	0.0005	0.0003	0.00007	16.6	0.14	0.012	0.0001
MK78	0.29	0.007	0.44	0.016	15.8	0.126	0.0006	0.00028	<0.06	<0.01	2.98	0.04	0.0009	0.00006	0.0003	0.0004	0.0002	0.00005	18.6	0.18	0.187	0.0013
MK79	0.64	0.013	0.86	0.026	30.7	0.235	0.0007	0.00024	<0.06	<0.01	2.93	0.04	0.0020	0.00013	0.0006	0.0007	0.0007	0.00012	21.4	0.19	0.016	0.0001
MK80	0.23	0.006	0.33	0.012	10.9	0.091	0.0059	0.00306	<0.06	<0.01	3.53	0.05	0.0018	0.00012	0.0001	0.0001	0.0009	0.00019	17.2	0.20	0.032	0.0002
MK81	0.17	0.004	1.04	0.038	17.3	0.149	0.0001	0.00006	<0.06	<0.01	1.63	0.02	0.0010	0.00006	0.0005	0.0007	0.0002	0.00005	15.9	0.16	0.034	0.0002
MK82	0.21	0.007	0.30	0.012	6.5	0.059	0.0012	0.00078	<0.06	<0.01	1.72	0.02	0.0010	0.00007	0.0011	0.0017	0.0004	0.00009	13.8	0.20	0.036	0.0002

Table A3.5 Physiological element concentrations (Con) in whole aboveground plants (mg kg^{-1}) and their transfer factors (TF) (n = 23)

Site	Al		Ca		Fe		K		Mg		Mn		Na		P		S		As		Ba	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
H1	7	0.00008	2685	1.22	188	0.0049	18401	0.83	1229	0.19	378	1.44	74	0.028	2911	4.08	1608	2.87	3.27	0.26	67	0.14
H5	<4	<0.00005	1667	0.78	53	0.0013	9980	0.48	2262	0.36	437	1.56	630	0.195	1963	3.94	946	1.97	1.57	0.09	53	0.11
H6	<4	<0.00005	2539	1.13	44	0.0016	9028	0.53	2888	0.59	630	2.65	43	0.015	1828	4.42	2104	7.06	0.49	0.04	61	0.15
H7	<4	<0.00005	1424	0.70	65	0.0022	13053	0.72	1515	0.28	291	1.25	202	0.068	2175	5.81	1821	5.07	1.63	0.13	65	0.15
HN1	45	0.00060	2838	0.34	88	0.0022	18963	0.90	2230	0.25	544	0.91	368	0.069	2905	3.44	1465	2.38	4.89	0.27	42	0.10
HN2	<4	<0.00005	2669	0.38	24	0.0007	15408	0.86	1650	0.22	210	0.29	43	0.008	2673	3.49	1026	6.28	0.96	0.06	27	0.07
HN3	<4	<0.00005	2478	0.39	41	0.0013	15504	0.85	1847	0.24	195	0.39	152	0.028	2657	3.42	1054	3.31	1.63	0.11	19	0.05
HN5	<4	<0.00005	2839	0.56	15	0.0004	12915	0.66	1950	0.23	271	0.52	13	0.002	2288	2.69	1257	2.91	0.61	0.03	39	0.10
HN6	<4	<0.00005	1750	0.44	27	0.0006	19756	0.91	1459	0.16	330	0.41	48	0.009	1731	2.52	928	3.28	1.11	0.05	42	0.10
HN7	<4	<0.00005	1993	0.63	45	0.0010	16476	0.69	1641	0.17	314	0.93	102	0.021	1748	2.96	1090	3.27	0.72	0.04	29	0.07
HN8	<4	<0.00005	2007	0.68	23	0.0005	11709	0.50	1717	0.18	413	1.21	72	0.014	1402	2.34	1133	3.18	0.52	0.03	61	0.14
HN9	<4	<0.00005	2263	0.64	42	0.0010	16344	0.70	1845	0.19	532	1.62	35	0.007	2200	2.28	1086	2.74	1.92	0.12	60	0.13
HN10	<4	<0.00005	1909	0.77	18	0.0003	17758	0.87	1667	0.35	1072	5.16	24	0.008	2291	3.13	1644	1.65	0.79	0.03	29	0.08
HN11	<4	<0.00005	1850	0.41	20	0.0005	21401	0.91	1543	0.16	250	0.39	54	0.010	2468	1.96	1215	4.84	1.40	0.06	26	0.06
PT1	<4	<0.00005	2066	0.44	27	0.0011	16857	1.45	1808	0.42	498	1.53	58	0.010	2210	2.35	1301	7.17	0.30	0.03	56	0.18
PT3	7	0.000112	1416	0.18	17	0.0005	18384	0.96	1696	0.19	159	0.29	98	0.013	2117	2.00	947	2.07	0.84	0.04	57	0.13
PT4	<4	<0.00005	2288	0.21	61	0.0015	17444	0.84	1647	0.16	47	0.06	11	0.001	1806	2.02	1166	6.47	0.16	0.00	25	0.05
PT6	<4	<0.00005	1336	0.45	38	0.0004	11113	1.00	2335	0.53	293	0.68	663	0.286	2848	4.79	1330	2.02	1.84	0.07	33	0.16
PT7	<4	<0.00005	3681	1.11	51	0.0006	10985	1.33	2307	0.68	177	0.61	153	0.078	2920	4.77	1904	2.87	2.38	0.13	26	0.16
PT8	7	0.000111	1855	0.26	45	0.0012	15498	0.83	1845	0.24	262	0.50	73	0.011	2728	2.58	1326	2.44	1.92	0.08	52	0.12
PT9	<4	<0.00005	2668	0.18	28	0.0008	14197	0.77	1445	0.16	174	0.24	40	0.006	2211	1.65	1304	2.85	1.06	0.04	31	0.07
PT10	<4	<0.00005	2603	0.50	80	0.0016	20642	0.83	1499	0.15	184	0.28	705	0.159	2634	3.19	1465	0.26	0.36	0.02	77	0.17
PT11	<4	<0.00005	2707	0.50	13	0.0003	14594	0.69	1862	0.29	311	0.54	70	0.022	2016	2.36	1474	2.54	0.53	0.03	53	0.14

Table A3.5 *(cont.)* Physiological element concentrations (Con) in whole aboveground plants (mg kg^{-1}) and their transfer factors (TF) (n = 23)

Site	Bi		Cd		Ce		Co		Cr		Cs		Cu		Hf		La		Li		Mo	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
H1	0.009	0.012	0.206	0.60	0.087	0.00084	0.581	0.033	0.46	0.010	0.15	0.019	2.91	0.08	0.012	0.0035	0.043	0.0009	0.055	0.0018	0.82	0.74
H5	0.002	0.004	0.498	2.27	0.110	0.00123	0.342	0.024	0.35	0.008	0.43	0.066	3.56	0.12	0.003	0.0008	0.053	0.0012	0.024	0.0008	0.29	0.24
H6	0.002	0.006	0.213	1.12	0.164	0.00260	0.458	0.046	0.38	0.012	1.68	0.344	4.71	0.23	0.001	0.0003	0.087	0.0025	0.070	0.0033	0.74	0.91
H7	0.005	0.011	0.103	0.51	0.048	0.00071	0.306	0.028	0.40	0.012	0.62	0.114	2.42	0.11	0.001	0.0002	0.025	0.0007	0.053	0.0023	0.73	0.80
HN1	0.010	0.020	0.075	0.22	0.094	0.00116	0.091	0.005	0.84	0.014	0.22	0.025	2.18	0.06	0.001	0.0001	0.040	0.0010	0.069	0.0016	0.53	0.76
HN2	0.006	0.013	0.041	0.14	0.409	0.00518	0.070	0.005	0.60	0.012	0.19	0.027	3.82	0.11	0.003	0.0006	0.218	0.0055	0.012	0.0003	0.51	1.24
HN3	0.008	0.017	0.043	0.13	0.025	0.00036	0.072	0.005	0.45	0.009	0.24	0.034	2.57	0.07	0.005	0.0011	0.010	0.0003	0.063	0.0017	1.11	2.62
HN5	0.004	0.009	0.071	0.19	0.033	0.00042	0.056	0.003	0.38	0.006	0.04	0.005	3.61	0.09	0.004	0.0010	0.037	0.0009	<0.006	<0.0001	0.36	0.69
HN6	0.005	0.012	0.219	0.59	0.011	0.00012	0.098	0.005	0.48	0.007	0.05	0.005	2.03	0.05	0.006	0.0012	0.047	0.0011	0.014	0.0003	0.49	0.73
HN7	0.004	0.009	0.228	0.70	0.022	0.00024	0.068	0.004	0.48	0.006	0.04	0.004	2.95	0.07	0.005	0.0010	0.013	0.0003	0.010	0.0002	0.48	0.76
HN8	0.003	0.007	0.535	1.74	0.044	0.00046	0.056	0.003	0.64	0.008	0.08	0.007	3.19	0.07	0.007	0.0015	0.004	0.0001	0.046	0.0009	0.26	0.44
HN9	0.006	0.010	0.785	2.12	0.037	0.00039	0.095	0.005	0.34	0.004	0.02	0.001	3.59	0.08	0.002	0.0003	0.020	0.0004	0.011	0.0002	0.30	0.57
HN10	0.002	0.004	1.892	5.87	0.036	0.00038	0.121	0.010	0.40	0.005	0.07	0.007	4.82	0.13	0.004	0.0008	0.010	0.0002	0.033	0.0008	0.15	0.11
HN11	0.004	0.006	0.096	0.30	0.032	0.00037	0.078	0.004	0.46	0.007	0.01	0.001	4.07	0.09	0.003	0.0006	0.016	0.0004	<0.006	<0.0001	0.88	1.27
PT1	0.003	0.008	0.254	1.06	0.004	0.00006	0.037	0.005	0.37	0.012	0.07	0.023	3.93	0.14	0.003	0.0006	0.001	0.0000	0.052	0.0028	0.99	2.14
PT3	0.002	0.002	0.062	0.13	0.004	0.00004	0.054	0.004	0.44	0.009	0.12	0.020	3.60	0.07	0.004	0.0008	0.005	0.0001	0.024	0.0007	0.64	0.83
PT4	0.002	0.001	0.063	0.11	0.047	0.00043	0.033	0.002	0.35	0.006	0.15	0.023	8.53	0.10	0.001	0.0004	0.051	0.0010	0.034	0.0010	0.64	0.47
PT6	0.005	0.009	0.039	0.10	0.069	0.00114	0.103	0.009	0.54	0.004	0.26	0.055	1.25	0.02	0.002	0.0012	0.190	0.0058	0.088	0.0039	0.15	0.07
PT7	0.006	0.011	0.047	0.23	0.054	0.00070	0.222	0.028	0.37	0.003	0.29	0.077	1.27	0.03	0.001	0.0006	0.027	0.0007	0.051	0.0027	0.36	0.15
PT8	0.005	0.004	0.100	0.22	0.010	0.00013	0.173	0.012	0.43	0.007	0.06	0.009	2.55	0.05	0.004	0.0010	0.007	0.0002	0.020	0.0006	0.77	0.89
PT9	0.005	0.004	0.054	0.11	0.035	0.00043	0.054	0.004	0.46	0.008	0.02	0.003	2.53	0.04	0.001	0.0004	0.020	0.0005	0.013	0.0004	0.73	0.93
PT10	0.004	0.006	0.024	0.05	0.010	0.00010	0.075	0.004	0.48	0.005	0.05	0.004	2.80	0.05	0.005	0.0011	0.006	0.0001	<0.006	<0.0001	0.14	0.11
PT11	0.005	0.007	0.195	0.40	0.030	0.00029	0.063	0.004	0.32	0.005	0.02	0.002	2.74	0.07	0.005	0.0013	0.031	0.0007	0.006	0.0002	0.39	0.38

Table A3.5 *(cont.)* Physiological element concentrations (Con) in whole aboveground plants (mg kg^{-1}) and their transfer factors (TF) (n = 23)

Site	Ni		Pb		Rb		Sb		Sn		Sr		Th		Tl		U		Zn		Zr	
	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF	Con	TF
H1	0.58	0.016	0.20	0.005	45	0.34	0.007	0.004	<0.06	<0.01	7.2	0.18	0.001	0.00005	0.011	0.016	0.0057	0.0011	51	0.45	0.05	0.0005
H5	0.42	0.013	0.12	0.004	87	0.71	0.005	0.003	<0.06	<0.01	7.6	0.18	0.001	0.00004	0.069	0.109	0.0015	0.0003	51	0.60	0.02	0.0002
H6	1.92	0.089	0.21	0.009	115	1.18	0.004	0.003	<0.06	<0.01	12.6	0.32	0.001	0.00004	0.147	0.301	0.0006	0.0002	28	0.43	0.01	0.0001
H7	0.49	0.020	0.05	0.002	118	1.12	0.004	0.003	<0.06	<0.01	6.3	0.16	0.001	0.00005	0.043	0.082	0.0026	0.0007	36	0.51	0.04	0.0004
HN1	0.36	0.008	0.51	0.014	7	0.06	0.039	0.021	<0.06	<0.01	9.7	0.12	0.004	0.00023	0.006	0.010	0.0560	0.0148	21	0.22	0.06	0.0004
HN2	0.33	0.009	0.32	0.010	30	0.27	0.014	0.008	<0.06	<0.01	7.9	0.10	0.025	0.00157	0.006	0.011	0.0010	0.0003	31	0.37	0.10	0.0006
HN3	0.17	0.005	0.51	0.015	23	0.20	0.021	0.013	0.07	0.02	8.0	0.10	0.004	0.00028	0.009	0.017	0.0012	0.0004	23	0.23	0.07	0.0006
HN5	0.29	0.007	0.26	0.008	21	0.18	0.008	0.004	<0.06	<0.01	7.3	0.10	0.004	0.00029	0.003	0.006	0.0009	0.0003	25	0.25	0.07	0.0005
HN6	0.33	0.007	0.38	0.010	40	0.31	0.013	0.006	<0.06	<0.01	4.7	0.06	0.003	0.00019	0.006	0.011	0.0022	0.0006	35	0.36	0.53	0.0035
HN7	0.32	0.006	0.33	0.008	32	0.23	0.010	0.005	<0.06	<0.01	4.7	0.06	0.002	0.00011	0.006	0.009	0.0013	0.0003	35	0.33	0.02	0.0002
HN8	0.48	0.010	0.44	0.010	30	0.21	0.009	0.004	<0.06	<0.01	6.2	0.08	0.001	0.00005	0.007	0.010	0.0005	0.0001	27	0.26	0.69	0.0045
HN9	0.55	0.011	0.65	0.014	13	0.09	0.012	0.006	4.22	0.95	6.8	0.08	0.002	0.00010	0.004	0.006	0.0021	0.0005	45	0.40	0.33	0.0022
HN10	0.85	0.024	0.30	0.008	33	0.24	0.004	0.001	1.52	0.32	5.2	0.06	0.002	0.00009	0.004	0.005	0.0014	0.0003	20	0.23	0.05	0.0003
HN11	0.57	0.012	0.81	0.019	20	0.14	0.009	0.005	0.69	0.13	4.0	0.05	0.013	0.00078	0.006	0.008	0.0048	0.0013	37	0.28	0.20	0.0014
PT1	0.67	0.036	0.36	0.009	82	1.27	0.083	0.080	<0.06	<0.01	7.5	0.10	0.023	0.00173	0.008	0.024	0.0015	0.0005	42	0.60	0.11	0.0008
PT3	0.14	0.004	0.13	0.002	109	1.03	0.005	0.003	<0.06	<0.01	5.2	0.06	0.005	0.00030	0.016	0.031	0.0012	0.0004	24	0.23	0.01	0.0001
PT4	0.54	0.014	0.28	0.003	21	0.18	0.007	0.002	<0.06	<0.01	4.5	0.04	0.041	0.00250	0.004	0.007	0.0003	0.0001	25	0.19	0.04	0.0003
PT6	0.17	0.006	0.35	0.006	56	0.86	0.016	0.012	<0.06	<0.01	5.1	0.15	0.108	0.00444	0.007	0.019	0.0034	0.0009	16	0.12	0.12	0.0019
PT7	0.43	0.019	0.45	0.009	39	0.80	0.015	0.013	<0.06	<0.01	11.0	0.37	0.002	0.00008	0.005	0.017	0.0017	0.0004	18	0.21	0.05	0.0011
PT8	0.16	0.005	0.32	0.004	40	0.38	0.012	0.005	<0.06	<0.01	6.2	0.06	0.003	0.00019	0.006	0.011	0.0009	0.0003	41	0.37	0.04	0.0004
PT9	0.12	0.004	0.40	0.005	25	0.23	0.012	0.006	<0.06	<0.01	8.1	0.08	0.000	0.00002	0.006	0.011	0.0016	0.0005	28	0.22	0.01	0.0001
PT10	0.49	0.009	0.38	0.008	11	0.08	0.011	0.006	2.16	0.41	10.0	0.13	0.002	0.00009	0.003	0.004	0.0080	0.0019	14	0.09	0.26	0.0019
PT11	0.21	0.006	0.57	0.011	23	0.17	0.008	0.003	1.64	0.24	6.4	0.15	0.003	0.00014	0.005	0.008	0.0005	0.0001	36	0.29	0.03	0.0002

Table A3.6 Indexes of non-cancer risk (HI) and cancer risk (∑ILCR) assessment in the river areas (n = 101)

Site	Area	As			Cd		Co		Cu		Mn		Mo		Ni		Pb			HI	∑ILCR
		CDI	THQ	ILCR	CDI	THQ	CDI	THQ	CDI	THQ	CDI	THQ	CDI	THQ	CDI	THQ	CDI	THQ	ILCR		
H1	Huong	0.0026	1.30	0.0039	0.00077	2.19	0.0005	0.35	0.023	0.12	0.16	0.81	0.0046	0.11	0.0051	0.26	0.0002	0.10	0.000001	5.2	0.0039
H5	Huong	0.0026	1.29	0.0039	0.00056	1.59	0.0005	0.33	0.029	0.15	0.18	0.90	0.0037	0.09	0.0029	0.15	<0.0002	<0.1	<0.000001	4.5	0.0039
H6	Huong	0.0010	0.50	0.0015	0.00096	2.73	0.0010	0.68	0.036	0.18	0.20	1.01	0.0059	0.15	0.0171	0.86	<0.0002	<0.1	<0.000001	6.1	0.0015
H7	Huong	0.0021	1.07	0.0032	0.00033	0.93	0.0005	0.32	0.021	0.11	0.18	0.89	0.0070	0.18	0.0040	0.20	<0.0002	<0.1	<0.000001	3.7	0.0032
HN1	Red	0.0026	1.31	0.0039	0.00004	0.10	0.0001	0.05	0.013	0.06	0.14	0.69	0.0033	0.08	0.0004	0.02	<0.0002	<0.1	<0.000001	2.3	0.0039
HN2	Red	0.0012	0.61	0.0018	0.00009	0.25	0.0002	0.14	0.035	0.17	0.17	0.87	0.0040	0.10	0.0028	0.14	<0.0002	<0.1	<0.000001	2.3	0.0018
HN3	Red	0.0020	1.02	0.0031	0.00007	0.20	0.0001	0.10	0.024	0.12	0.15	0.75	0.0099	0.25	0.0009	0.04	<0.0002	<0.1	<0.000001	2.5	0.0031
HN5	Red	0.0010	0.52	0.0015	0.00026	0.74	0.0002	0.10	0.032	0.16	0.18	0.88	0.0036	0.09	0.0026	0.13	<0.0002	<0.1	<0.000001	2.6	0.0015
HN6	Red	0.0017	0.86	0.0026	0.00099	2.82	0.0002	0.10	0.016	0.08	0.22	1.12	0.0056	0.14	0.0034	0.17	<0.0002	<0.1	<0.000001	5.3	0.0026
HN7	Red	0.0013	0.63	0.0019	0.00097	2.78	0.0001	0.08	0.026	0.13	0.17	0.86	0.0054	0.13	0.0033	0.17	<0.0002	<0.1	<0.000001	4.8	0.0019
HN8	Red	0.0008	0.41	0.0012	0.00202	5.77	0.0001	0.04	0.029	0.14	0.15	0.76	0.0034	0.09	0.0068	0.34	<0.0002	<0.1	<0.000001	7.5	0.0012
HN9	Red	0.0021	1.04	0.0031	0.00247	7.05	0.0002	0.10	0.030	0.15	0.22	1.12	0.0042	0.10	0.0048	0.24	<0.0002	<0.1	<0.000001	9.8	0.0031
HN10	Red	0.0014	0.72	0.0021	0.00738	21.1	0.0002	0.16	0.034	0.17	0.35	1.74	0.0017	0.04	0.0078	0.39	<0.0002	<0.1	<0.000001	24.3	0.0021
HN11	Red	0.0016	0.78	0.0023	0.00038	1.09	0.0002	0.11	0.032	0.16	0.20	1.00	0.0068	0.17	0.0024	0.12	<0.0002	<0.1	<0.000001	3.4	0.0023
PT1	Red	0.0010	0.49	0.0015	0.00113	3.24	0.0001	0.04	0.033	0.17	0.18	0.92	0.0072	0.18	0.0064	0.32	<0.0002	<0.1	<0.000001	5.4	0.0015
PT3	Red	0.0020	0.99	0.0030	0.00023	0.66	0.0001	0.06	0.033	0.16	0.13	0.66	0.0065	0.16	0.0010	0.05	<0.0002	<0.1	<0.000001	2.7	0.0030
PT4	Red	0.0010	0.48	0.0014	0.00022	0.64	0.0001	0.08	0.065	0.33	0.09	0.44	0.0055	0.14	0.0064	0.32	<0.0002	<0.1	<0.000001	2.4	0.0014
PT6	Red	0.0020	0.99	0.0030	0.00002	0.06	0.0000	0.03	0.006	0.03	0.13	0.65	0.0015	0.04	0.0002	0.01	<0.0002	<0.1	<0.000001	1.8	0.0030
PT7	Red	0.0026	1.29	0.0039	0.00003	0.08	0.0000	0.03	0.005	0.03	0.14	0.69	0.0019	0.05	0.0004	0.02	<0.0002	<0.1	<0.000001	2.2	0.0039
PT8	Red	0.0021	1.05	0.0031	0.00031	0.88	0.0002	0.12	0.021	0.11	0.18	0.91	0.0091	0.23	0.0006	0.03	<0.0002	<0.1	<0.000001	3.3	0.0031
PT9	Red	0.0017	0.87	0.0026	0.00020	0.57	0.0001	0.07	0.022	0.11	0.14	0.69	0.0090	0.23	0.0006	0.03	<0.0002	<0.1	<0.000001	2.6	0.0026
PT10	Red	0.0012	0.61	0.0018	0.00002	0.05	0.0000	0.02	0.007	0.03	0.12	0.61	0.0014	0.03	0.0006	0.03	<0.0002	<0.1	<0.000001	1.4	0.0018
PT11	Red	0.0010	0.52	0.0016	0.00060	1.71	0.0001	0.07	0.024	0.12	0.16	0.81	0.0036	0.09	0.0016	0.08	<0.0002	<0.1	<0.000001	3.4	0.0016
MK-1	Mekong	0.0008	0.38	0.0011	0.00002	0.06	0.0001	0.05	0.021	0.10	0.12	0.58	0.0031	0.08	0.0007	0.04	0.0012	0.80	0.000010	2.1	0.0011
MK-2	Mekong	0.0012	0.58	0.0017	0.00049	1.41	0.0001	0.06	0.021	0.10	0.17	0.84	0.0078	0.20	0.0012	0.06	0.0025	1.69	0.000022	4.9	0.0018
MK-3	Mekong	0.0009	0.44	0.0013	0.00016	0.46	0.0001	0.07	0.024	0.12	0.16	0.81	0.0025	0.06	0.0016	0.08	0.0009	0.61	0.000008	2.6	0.0013
MK-4	Mekong	0.0009	0.44	0.0013	0.00020	0.57	0.0002	0.11	0.038	0.19	0.19	0.95	0.0034	0.08	0.0025	0.12	0.0028	1.89	0.000024	4.4	0.0013
MK-5	Mekong	0.0010	0.50	0.0015	0.00015	0.43	0.0002	0.11	0.024	0.12	0.14	0.71	0.0023	0.06	0.0014	0.07	0.0012	0.77	0.000010	2.8	0.0015
MK-6	Mekong	0.0008	0.42	0.0013	0.00020	0.56	0.0002	0.14	0.078	0.39	0.17	0.85	0.0025	0.06	0.0020	0.10	0.0036	2.40	0.000031	4.9	0.0013
MK-7	Mekong	0.0014	0.69	0.0021	0.00004	0.11	0.0001	0.06	0.026	0.13	0.14	0.72	0.0046	0.11	0.0005	0.03	0.0013	0.87	0.000011	2.7	0.0021
MK-8	Mekong	0.0015	0.76	0.0023	0.00029	0.84	0.0002	0.16	0.035	0.18	0.22	1.09	0.0027	0.07	0.0030	0.15	0.0021	1.41	0.000018	4.7	0.0023
MK-9	Mekong	0.0017	0.86	0.0026	0.00006	0.16	0.0001	0.07	0.031	0.15	0.18	0.88	0.0037	0.09	0.0010	0.05	0.0008	0.55	0.000007	2.8	0.0026
MK10	Mekong	0.0027	1.35	0.0040	0.00003	0.08	0.0001	0.06	0.008	0.04	0.11	0.54	0.0022	0.06	0.0002	0.01	0.0018	1.17	0.000015	3.3	0.0041
MK11	Mekong	0.0024	1.19	0.0036	0.00036	1.02	0.0001	0.10	0.021	0.10	0.17	0.85	0.0034	0.08	0.0023	0.11	0.0007	0.45	0.000006	3.9	0.0036
MK12	Mekong	0.0032	1.62	0.0049	0.00002	0.07	0.0002	0.12	0.016	0.08	0.15	0.74	0.0032	0.08	0.0005	0.03	0.0016	1.07	0.000014	3.8	0.0049
MK13	Mekong	0.0021	1.03	0.0031	0.00006	0.18	0.0002	0.12	0.011	0.06	0.16	0.80	0.0031	0.08	0.0006	0.03	0.0024	1.58	0.000020	3.9	0.0031

CDI: Chronic Daily Intake (mg kg^{-1} b.w. day^{-1}); THQ: Target Hazard Quotient; and HI: Chronic Hazard Index; ILCR: Incremental Lifetime Cancer Risk; ∑ILCR: Cumulative Cancer Risk

Table A3.6 (*cont.*) Indexes of non-cancer risk (HI) and cancer risk (∑ILCR) assessment in the river areas (n = 101)

Site	**Area**	**As**			**Cd**		**Co**		**Cu**		**Mn**		**Mo**		**Ni**		**Pb**			**HI**	**∑ILCR**
		CDI	THQ	ILCR	CDI	THQ	CDI	THQ	CDI	THQ	CDI	THQ	CDI	THQ	CDI	THQ	CDI	THQ	ILCR		
MK14	Mekong	0.0024	1.18	0.0036	0.00005	0.15	0.0001	0.09	0.013	0.06	0.15	0.77	0.0031	0.08	0.0008	0.04	0.0009	0.61	0.000008	3.0	0.0036
MK15	Mekong	0.0021	1.03	0.0031	0.00016	0.47	0.0002	0.12	0.020	0.10	0.14	0.71	0.0027	0.07	0.0012	0.06	0.0009	0.63	0.000008	3.2	0.0031
MK16	Mekong	0.0013	0.67	0.0020	0.00019	0.54	0.0002	0.10	0.021	0.11	0.11	0.56	0.0024	0.06	0.0020	0.10	0.0002	0.16	0.000002	2.3	0.0020
MK17	Mekong	0.0015	0.73	0.0022	0.00042	1.21	0.0002	0.11	0.046	0.23	0.19	0.95	0.0021	0.05	0.0045	0.23	0.0012	0.81	0.000010	4.3	0.0022
MK18	Mekong	0.0019	0.93	0.0028	0.00026	0.76	0.0001	0.09	0.018	0.09	0.16	0.81	0.0030	0.08	0.0016	0.08	0.0004	0.29	0.000004	3.1	0.0028
MK19	Mekong	0.0043	2.14	0.0064	0.00002	0.05	0.0002	0.16	0.018	0.09	0.16	0.80	0.0046	0.12	0.0005	0.02	0.0003	0.20	0.000003	3.6	0.0064
MK20	Mekong	0.0022	1.11	0.0033	0.00007	0.19	0.0001	0.08	0.013	0.06	0.15	0.75	0.0029	0.07	0.0009	0.04	0.0021	1.39	0.000018	3.7	0.0034
MK21	Mekong	0.0015	0.74	0.0022	0.00054	1.54	0.0002	0.13	0.016	0.08	0.18	0.91	0.0032	0.08	0.0015	0.08	0.0022	1.49	0.000019	5.0	0.0022
MK22	Mekong	0.0009	0.47	0.0014	0.00053	1.53	0.0001	0.08	0.025	0.12	0.20	0.99	0.0046	0.12	0.0018	0.09	0.0005	0.34	0.000004	3.7	0.0014
MK23	Mekong	0.0010	0.48	0.0014	0.00027	0.78	0.0001	0.04	0.020	0.10	0.11	0.56	0.0036	0.09	0.0009	0.04	0.0006	0.40	0.000005	2.5	0.0015
MK24	Mekong	0.0013	0.64	0.0019	0.00040	1.15	0.0001	0.08	0.025	0.13	0.16	0.79	0.0038	0.10	0.0026	0.13	0.0003	0.18	0.000002	3.2	0.0019
MK25	Mekong	0.0010	0.51	0.0015	0.00143	4.08	0.0003	0.19	0.029	0.15	0.19	0.95	0.0031	0.08	0.0036	0.18	0.0006	0.40	0.000005	6.5	0.0015
MK26	Mekong	0.0013	0.65	0.0020	0.00009	0.25	0.0001	0.08	0.014	0.07	0.12	0.61	0.0031	0.08	0.0012	0.06	0.0004	0.23	0.000003	2.0	0.0020
MK27	Mekong	0.0012	0.59	0.0018	0.00016	0.45	0.0002	0.13	0.020	0.10	0.22	1.08	0.0025	0.06	0.0025	0.12	0.0002	0.17	0.000002	2.7	0.0018
MK30	Mekong	0.0018	0.88	0.0026	0.00004	0.11	0.0001	0.06	0.026	0.13	0.16	0.80	0.0025	0.06	0.0021	0.11	0.0008	0.52	0.000007	2.7	0.0027
MK31	Mekong	0.0021	1.06	0.0032	0.00009	0.27	0.0002	0.10	0.026	0.13	0.17	0.87	0.0036	0.09	0.0011	0.06	0.0003	0.18	0.000002	2.8	0.0032
MK32	Mekong	0.0020	0.99	0.0030	0.00003	0.09	0.0002	0.12	0.020	0.10	0.14	0.69	0.0043	0.11	0.0009	0.04	0.0071	4.73	0.000060	6.9	0.0030
MK33	Mekong	0.0018	0.90	0.0027	0.00011	0.31	0.0002	0.11	0.016	0.08	0.14	0.69	0.0070	0.17	0.0011	0.05	0.0012	0.77	0.000010	3.1	0.0027
MK34	Mekong	0.0009	0.43	0.0013	0.00083	2.38	0.0002	0.13	0.031	0.16	0.19	0.96	0.0014	0.04	0.0049	0.24	0.0011	0.73	0.000009	5.1	0.0013
MK35	Mekong	0.0012	0.62	0.0019	0.00011	0.31	0.0001	0.08	0.019	0.10	0.16	0.80	0.0018	0.05	0.0008	0.04	0.0042	2.82	0.000036	4.8	0.0019
MK36	Mekong	0.0006	0.30	0.0009	0.00050	1.43	0.0002	0.15	0.044	0.22	0.18	0.92	0.0039	0.10	0.0036	0.18	0.0009	0.63	0.000008	3.9	0.0009
MK37	Mekong	0.0010	0.52	0.0016	0.00066	1.90	0.0003	0.20	0.028	0.14	0.18	0.91	0.0078	0.19	0.0032	0.16	0.0066	4.38	0.000056	8.4	0.0016
MK38	Mekong	0.0014	0.70	0.0021	0.00015	0.42	0.0001	0.06	0.020	0.10	0.10	0.50	0.0032	0.08	0.0014	0.07	0.0003	0.17	0.000002	2.1	0.0021
MK40	Mekong	0.0019	0.96	0.0029	0.00047	1.35	0.0002	0.10	0.019	0.09	0.18	0.89	0.0034	0.08	0.0014	0.07	0.0010	0.65	0.000008	4.2	0.0029
MK41	Mekong	0.0017	0.83	0.0025	0.00014	0.40	0.0002	0.16	0.014	0.07	0.16	0.82	0.0035	0.09	0.0127	0.63	0.0011	0.77	0.000010	3.8	0.0025
MK42	Mekong	0.0013	0.65	0.0019	0.00032	0.93	0.0002	0.13	0.028	0.14	0.16	0.81	0.0028	0.07	0.0028	0.14	0.0009	0.62	0.000008	3.5	0.0020
MK43	Mekong	0.0010	0.49	0.0015	0.00043	1.24	0.0004	0.28	0.024	0.12	0.19	0.93	0.0025	0.06	0.0061	0.31	0.0003	0.17	0.000002	3.6	0.0015
MK44	Mekong	0.0012	0.58	0.0018	0.00023	0.66	0.0002	0.11	0.020	0.10	0.11	0.54	0.0043	0.11	0.0024	0.12	0.0004	0.27	0.000003	2.5	0.0018
MK45	Mekong	0.0015	0.77	0.0023	0.00019	0.55	0.0001	0.06	0.023	0.11	0.14	0.68	0.0017	0.04	0.0020	0.10	0.0007	0.45	0.000006	2.8	0.0023
MK46	Mekong	0.0017	0.85	0.0025	0.00003	0.08	0.0001	0.05	0.015	0.07	0.11	0.56	0.0010	0.03	0.0013	0.07	0.0004	0.30	0.000004	2.0	0.0025
MK47	Mekong	0.0019	0.94	0.0028	0.00008	0.22	0.0001	0.10	0.010	0.05	0.19	0.95	0.0025	0.06	0.0048	0.24	0.0003	0.21	0.000003	2.8	0.0028
MK48	Mekong	0.0013	0.65	0.0020	0.00038	1.08	0.0004	0.24	0.030	0.15	0.12	0.60	0.0040	0.10	0.0111	0.55	0.0002	0.12	0.000002	3.5	0.0020
MK49	Mekong	0.0012	0.62	0.0019	0.00028	0.79	0.0002	0.12	0.029	0.14	0.15	0.75	0.0016	0.04	0.0031	0.15	0.0068	4.51	0.000058	7.1	0.0019
MK51	Mekong	0.0029	1.43	0.0043	0.00002	0.06	0.0002	0.12	0.011	0.05	0.15	0.76	0.0041	0.10	0.0011	0.05	0.0015	1.00	0.000013	3.6	0.0043
MK52	Mekong	0.0009	0.47	0.0014	0.00011	0.31	0.0006	0.39	0.022	0.11	0.14	0.71	0.0013	0.03	0.0046	0.23	0.0015	1.00	0.000013	3.3	0.0014
MK53	Mekong	0.0017	0.85	0.0026	0.00032	0.92	0.0002	0.12	0.029	0.15	0.13	0.66	0.0021	0.05	0.0019	0.09	0.0005	0.36	0.000005	3.2	0.0026

CDI: Chronic Daily Intake (mg kg^{-1} b.w. day^{-1}); THQ: Target Hazard Quotient; and HI: Chronic Hazard Index; ILCR: Incremental Lifetime Cancer Risk; ∑ILCR: Cumulative Cancer Risk

Table A3.6 Indexes of non-cancer risk (HI) and cancer risk (∑ILCR) assessment in the river areas (n = 101)

Site	Area	As			Cd		Co		Cu		Mn		Mo		Ni		Pb			HI	∑ILCR
		CDI	THQ	ILCR	CDI	THQ	CDI	THQ	CDI	THQ	CDI	THQ	CDI	THQ	CDI	THQ	CDI	THQ	ILCR		
MK54	Mekong	0.0013	0.67	0.0020	0.00029	0.83	0.0002	0.16	0.026	0.13	0.18	0.88	0.0037	0.09	0.0033	0.17	0.0012	0.81	0.000010	3.7	0.0020
MK55	Mekong	0.0019	0.97	0.0029	0.00003	0.07	0.0002	0.14	0.053	0.26	0.17	0.84	0.0031	0.08	0.0018	0.09	0.0010	0.70	0.000009	3.2	0.0029
MK56	Mekong	0.0011	0.53	0.0016	0.00035	1.01	0.0002	0.12	0.024	0.12	0.14	0.69	0.0036	0.09	0.0039	0.20	0.0014	0.96	0.000012	3.7	0.0016
MK57	Mekong	0.0015	0.73	0.0022	0.00017	0.50	0.0001	0.09	0.024	0.12	0.16	0.80	0.0031	0.08	0.0016	0.08	0.0015	1.03	0.000013	3.4	0.0022
MK58	Mekong	0.0011	0.54	0.0016	0.00010	0.29	0.0001	0.09	0.030	0.15	0.19	0.94	0.0025	0.06	0.0021	0.10	0.0010	0.63	0.000008	2.8	0.0016
MK59	Mekong	0.0009	0.43	0.0013	0.00008	0.23	0.0001	0.09	0.028	0.14	0.11	0.56	0.0039	0.10	0.0024	0.12	0.0022	1.45	0.000018	3.1	0.0013
MK60	Mekong	0.0014	0.71	0.0021	0.00042	1.20	0.0002	0.10	0.023	0.11	0.18	0.89	0.0042	0.11	0.0026	0.13	0.0002	0.15	0.000002	3.4	0.0021
MK61	Mekong	0.0010	0.49	0.0015	0.00087	2.49	0.0002	0.15	0.028	0.14	0.20	1.01	0.0029	0.07	0.0046	0.23	0.0003	0.18	0.000002	4.8	0.0015
MK62	Mekong	0.0010	0.51	0.0015	0.00042	1.19	0.0001	0.07	0.020	0.10	0.18	0.89	0.0028	0.07	0.0016	0.08	0.0003	0.20	0.000003	3.1	0.0015
MK63	Mekong	0.0018	0.90	0.0027	0.00038	1.08	0.0005	0.32	0.024	0.12	0.16	0.78	0.0021	0.05	0.0226	1.13	0.0032	2.12	0.000027	6.5	0.0027
MK64	Mekong	0.0007	0.33	0.0010	0.00075	2.15	0.0009	0.59	0.038	0.19	0.19	0.94	0.0010	0.02	0.0160	0.80	0.0002	0.14	0.000002	5.2	0.0010
MK65	Mekong	0.0010	0.50	0.0015	0.00002	0.06	0.0001	0.06	0.011	0.05	0.11	0.57	0.0008	0.02	0.0020	0.10	0.0004	0.28	0.000004	1.6	0.0015
MK66	Mekong	0.0016	0.82	0.0025	0.00001	0.03	0.0001	0.07	0.011	0.05	0.12	0.59	0.0009	0.02	0.0023	0.12	0.0039	2.60	0.000033	4.3	0.0025
MK67	Mekong	0.0008	0.42	0.0013	0.00124	3.54	0.0002	0.13	0.041	0.20	0.20	0.98	0.0032	0.08	0.0031	0.15	0.0002	0.15	0.000002	5.7	0.0013
MK68	Mekong	0.0009	0.47	0.0014	0.00135	3.87	0.0002	0.13	0.033	0.17	0.21	1.03	0.0032	0.08	0.0027	0.14	0.0004	0.30	0.000004	6.2	0.0014
MK69	Mekong	0.0006	0.29	0.0009	0.00082	2.33	0.0001	0.07	0.043	0.22	0.16	0.82	0.0030	0.08	0.0047	0.24	0.0045	3.02	0.000039	7.1	0.0009
MK70	Mekong	0.0007	0.37	0.0011	0.00021	0.60	0.0001	0.05	0.017	0.09	0.18	0.90	0.0022	0.05	0.0008	0.04	0.0004	0.26	0.000003	2.4	0.0011
MK71	Mekong	0.0007	0.34	0.0010	0.00027	0.78	0.0001	0.05	0.020	0.10	0.21	1.03	0.0027	0.07	0.0010	0.05	0.0023	1.55	0.000020	4.0	0.0011
MK72	Mekong	0.0008	0.40	0.0012	0.00019	0.53	0.0001	0.09	0.032	0.16	0.13	0.64	0.0063	0.16	0.0021	0.11	0.0006	0.39	0.000005	2.5	0.0012
MK73	Mekong	0.0006	0.32	0.0010	0.00023	0.66	0.0002	0.13	0.032	0.16	0.17	0.86	0.0046	0.12	0.0027	0.14	0.0002	0.10	0.000001	2.5	0.0010
MK74	Mekong	0.0010	0.48	0.0014	0.00012	0.36	0.0002	0.12	0.033	0.17	0.19	0.97	0.0031	0.08	0.0026	0.13	0.0006	0.39	0.000005	2.7	0.0014
MK75	Mekong	0.0009	0.45	0.0013	0.00012	0.33	0.0002	0.15	0.023	0.12	0.19	0.93	0.0040	0.10	0.0016	0.08	0.0005	0.35	0.000004	2.5	0.0013
MK76	Mekong	0.0011	0.54	0.0016	0.00007	0.19	0.0001	0.10	0.027	0.13	0.12	0.60	0.0025	0.06	0.0034	0.17	0.0005	0.31	0.000004	2.1	0.0016
MK77	Mekong	0.0031	1.55	0.0047	0.00018	0.50	0.0003	0.17	0.018	0.09	0.11	0.57	0.0035	0.09	0.0040	0.20	0.0004	0.24	0.000003	3.4	0.0047
MK78	Mekong	0.0013	0.66	0.0020	0.00014	0.40	0.0003	0.21	0.031	0.15	0.13	0.63	0.0041	0.10	0.0029	0.15	0.0004	0.29	0.000004	2.6	0.0020
MK79	Mekong	0.0008	0.42	0.0012	0.00029	0.81	0.0004	0.24	0.027	0.14	0.14	0.70	0.0042	0.11	0.0073	0.37	0.0003	0.18	0.000002	3.0	0.0013
MK80	Mekong	0.0006	0.32	0.0010	0.00054	1.54	0.0003	0.19	0.034	0.17	0.19	0.96	0.0027	0.07	0.0046	0.23	0.0004	0.25	0.000003	3.7	0.0010
MK81	Mekong	0.0012	0.61	0.0018	0.00010	0.28	0.0002	0.11	0.013	0.07	0.13	0.65	0.0024	0.06	0.0029	0.15	0.0007	0.44	0.000006	2.4	0.0018
MK82	Mekong	0.0008	0.39	0.0012	0.00018	0.51	0.0006	0.37	0.027	0.13	0.14	0.71	0.0013	0.03	0.0090	0.45	0.0002	0.14	0.000002	2.7	0.0012

CDI: Chronic Daily Intake (mg kg^{-1} b.w. day^{-1}); THQ: Target Hazard Quotient; and HI: Chronic Hazard Index; ILCR: Incremental Lifetime Cancer Risk; ∑ILCR: Cumulative Cancer Risk

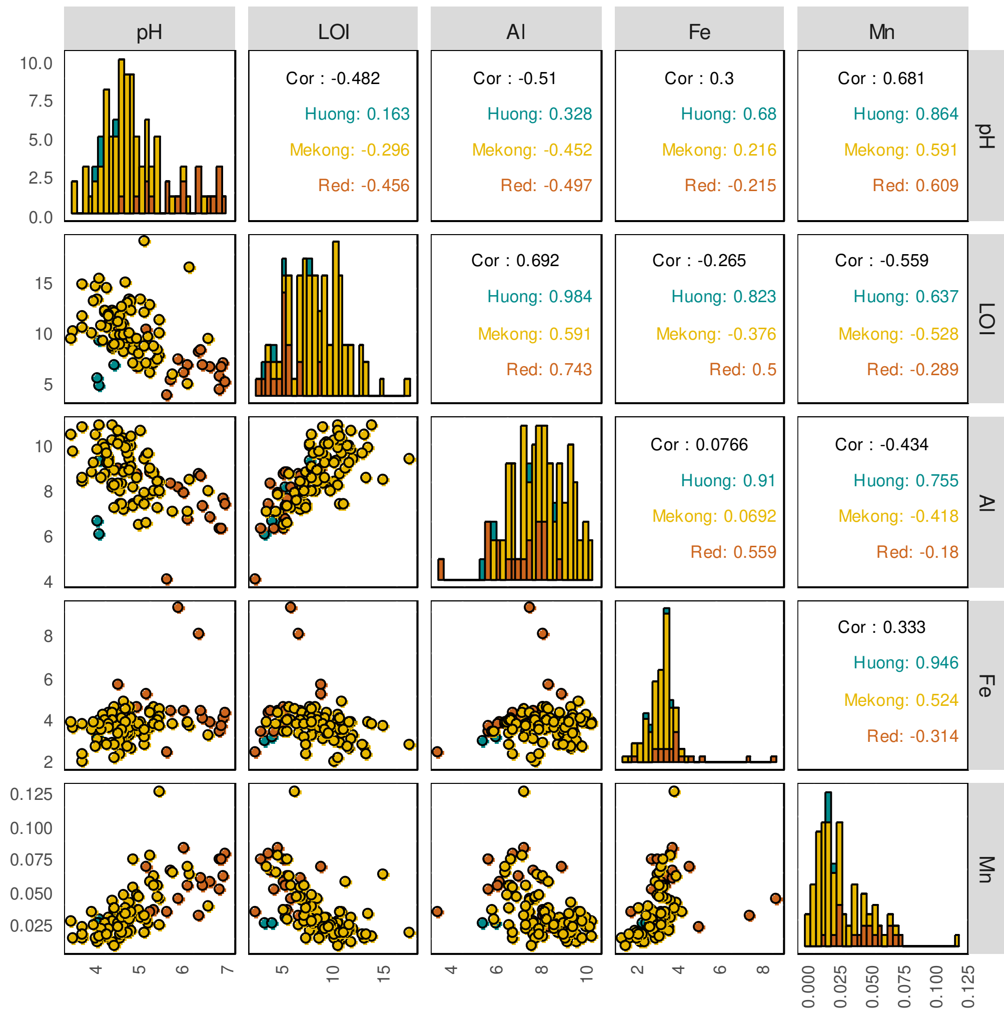


Fig. A3.1 Correlation matrix of the soil parameters pH, LOI, Al, Fe, and Mn (wt. %) in the different river area

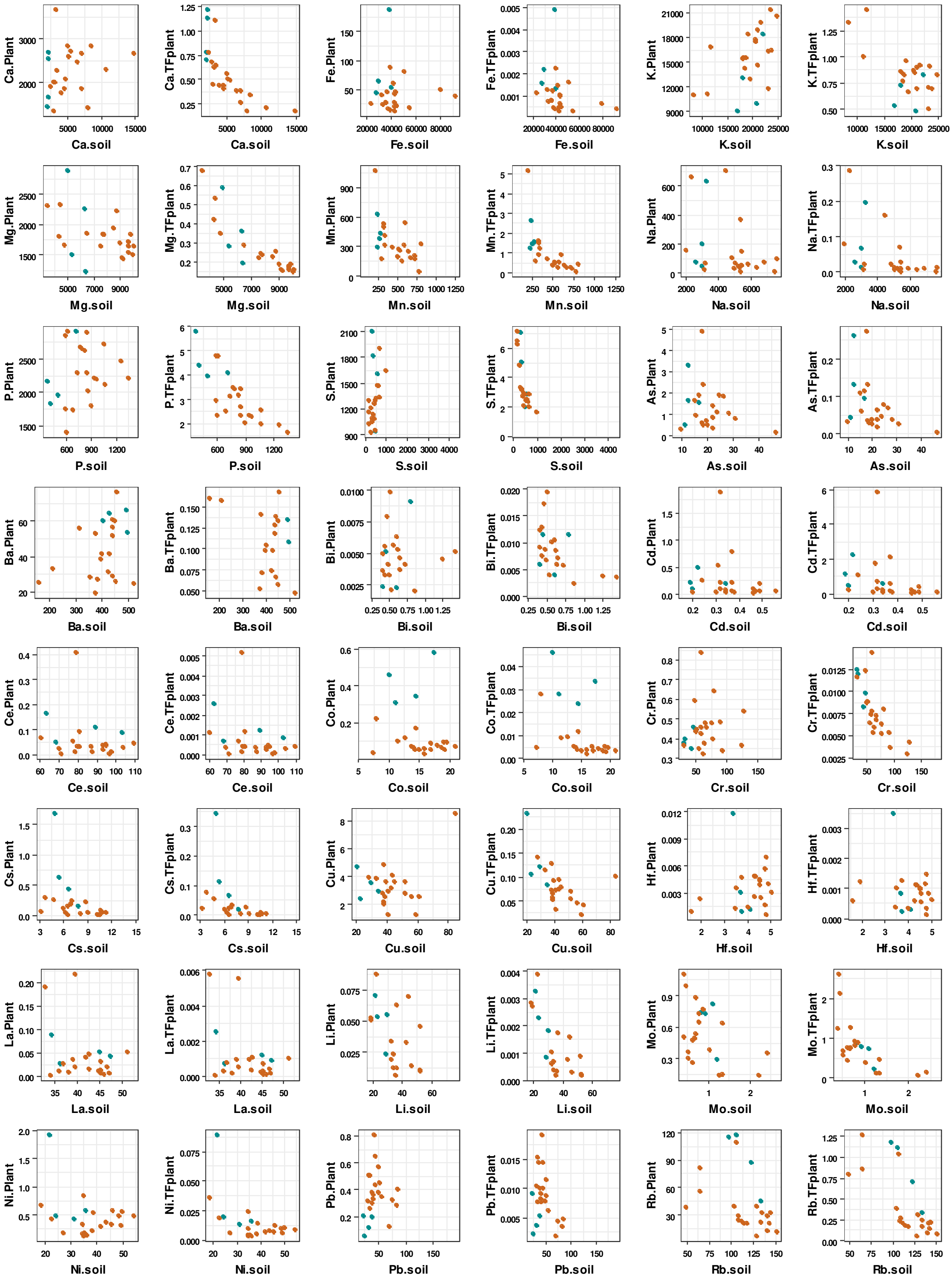


Fig. A3.2 Correlation plots of plant element concentrations (mg kg^{-1}) and plant transfer factors versus their soil concentrations (mg kg^{-1}). The red dots represent the Red River samples, the blue dots the Huong River samples

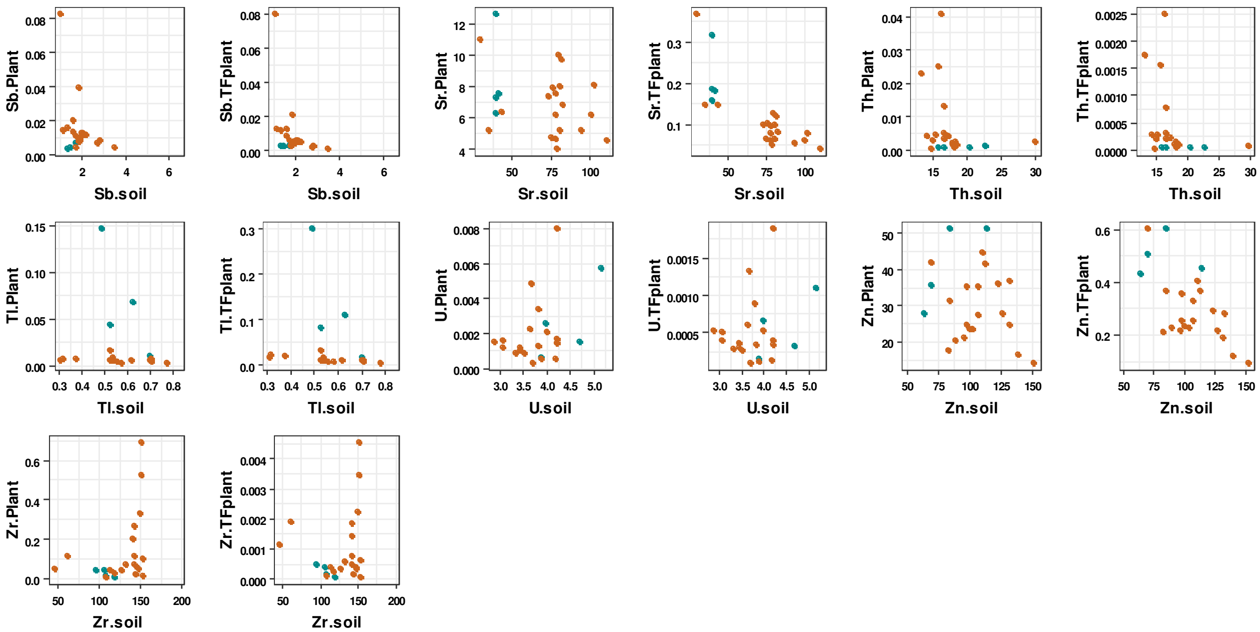


Fig. A3.2 (*cont.*) Correlation plots of plant element concentrations (mg kg^{-1}) and plant transfer factors versus their soil concentrations (mg kg^{-1}). The red dots represent the Red River samples, the blue dots the Huong River samples

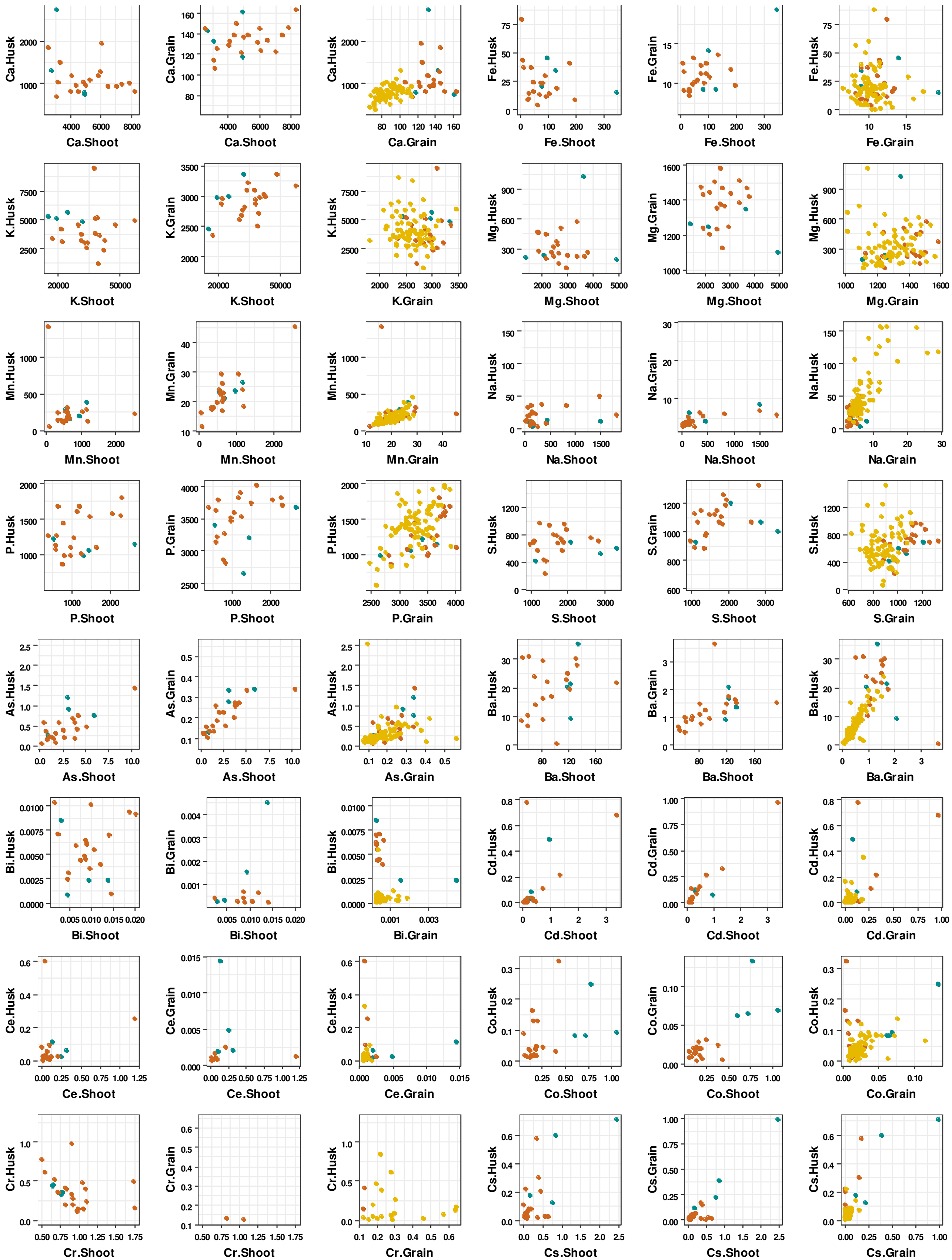


Fig. A3.3 Correlation plots between element concentrations in grain, husk and shoot (mg kg^{-1}). The red dots represent Red River samples, the blue dots the Huong River samples, and the yellow dots the Mekong samples

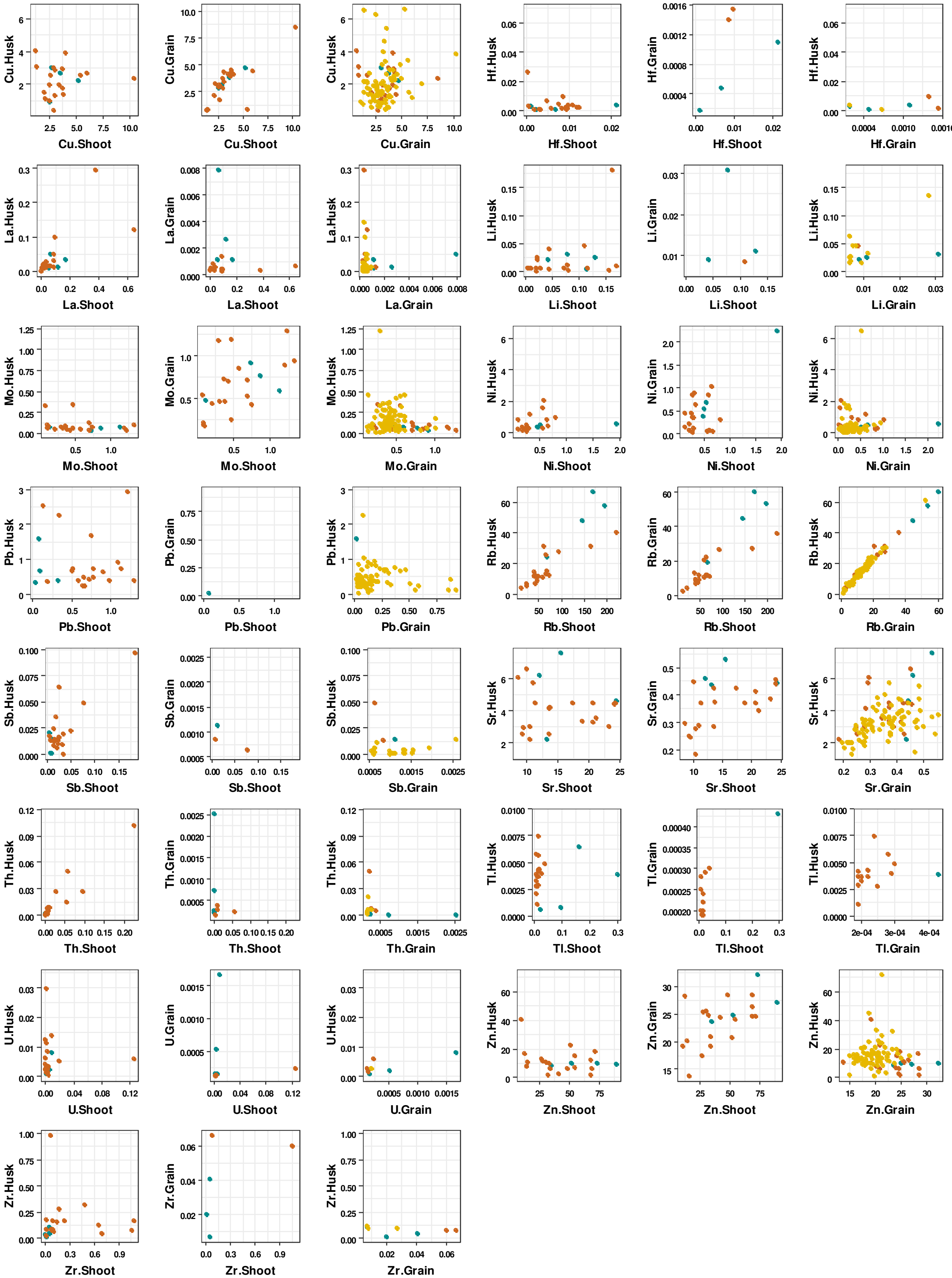
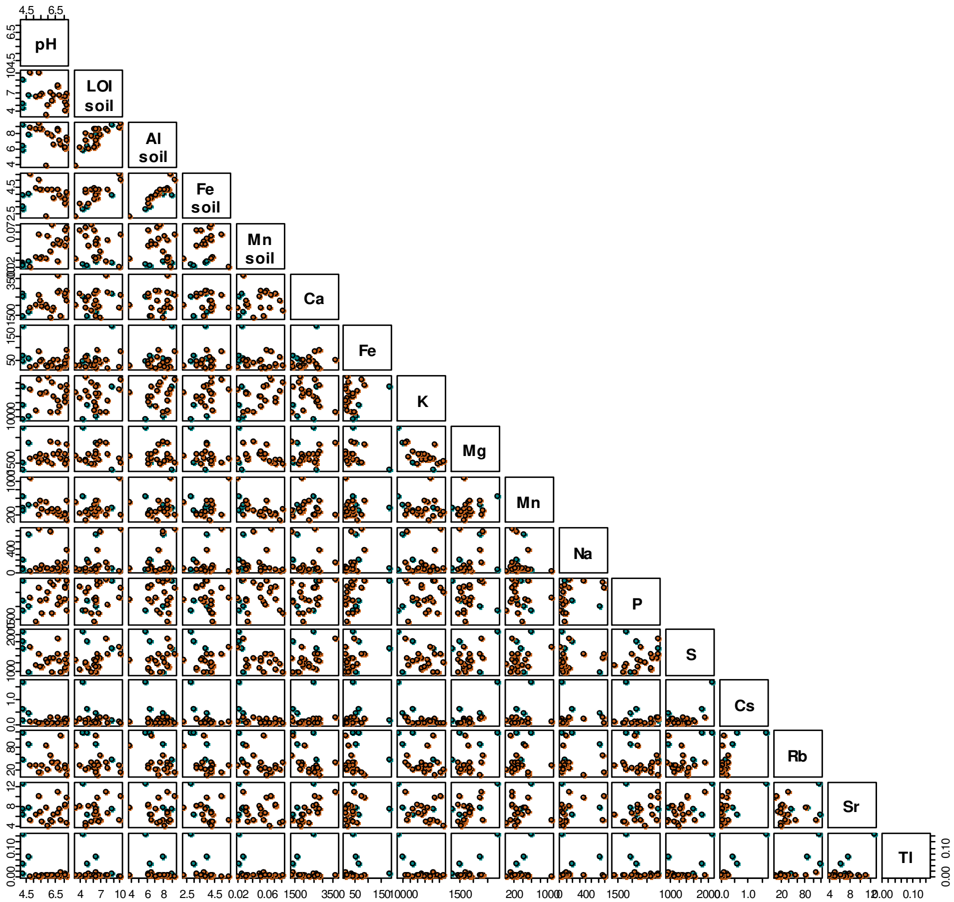


Fig. A3.3 (*cont.*) Correlation plots between element concentrations in grain, husk and shoot (mg kg^{-1}). The red dots represent Red River samples, the blue dots the Huong River samples, and the yellow dots the Mekong samples



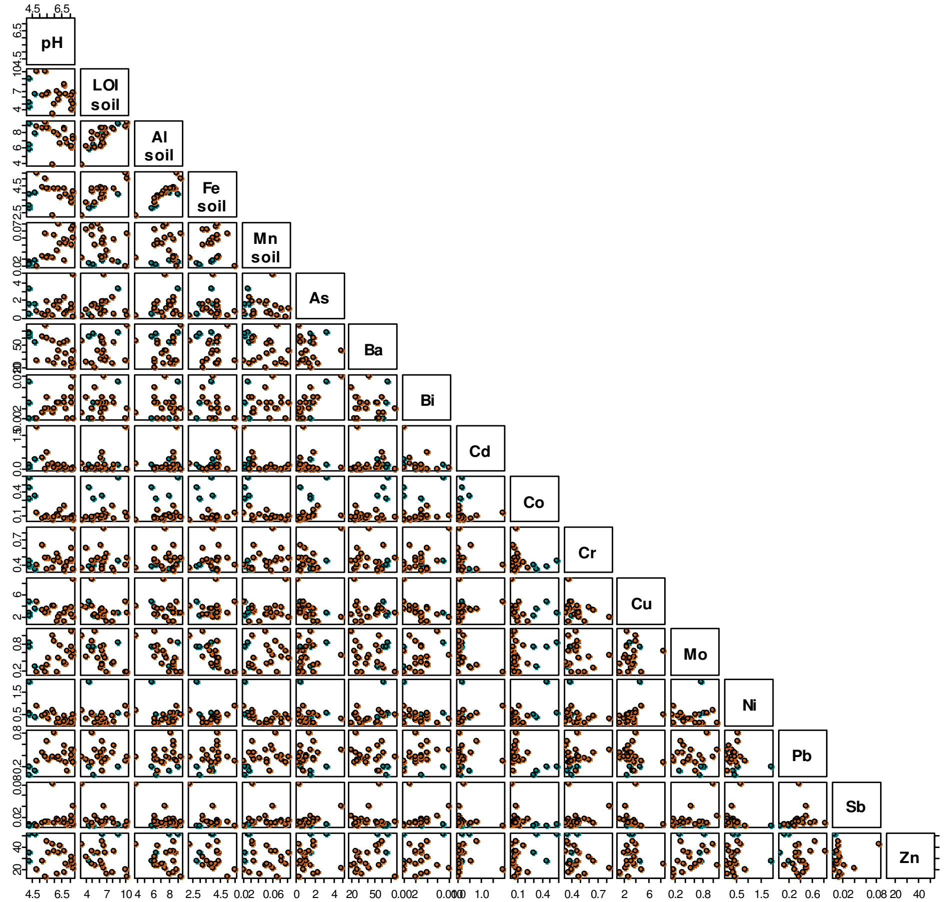


Fig. A3.4 Correlation plot matrix between plant element concentrations (mg kg^{-1}) and soil parameters (pH, LOI, Al, Fe, and Mn in wt. %)

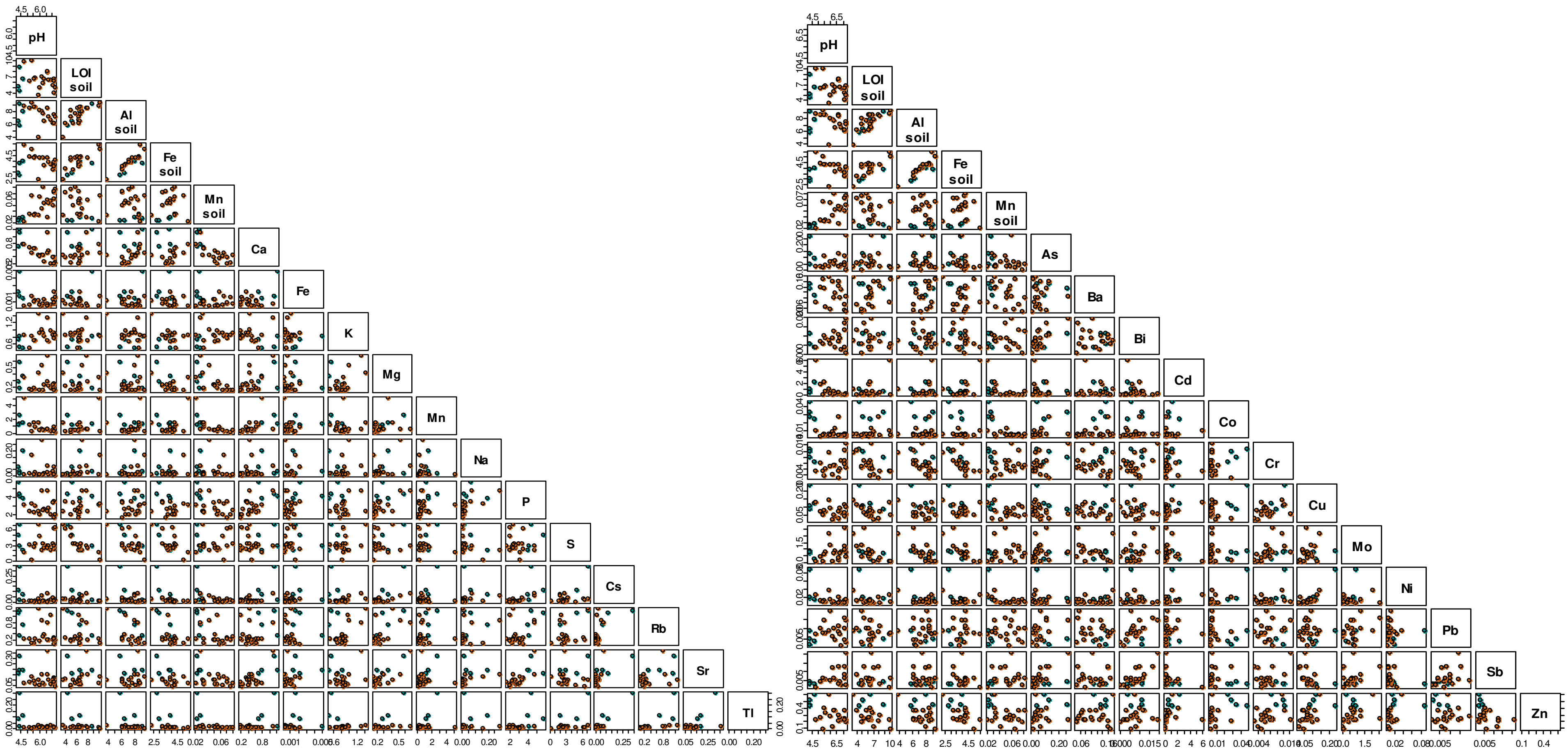


Fig. A3.5 Correlation plot matrix between plant transfer factors and soil parameters (pH, LOI, Al, Fe, and Mn in wt. %)

Curriculum Vitae

1. Personal information

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2. Academic background

2004 - 2008: Bachelor of Organic Chemistry, Hue University of Sciences, Viet Nam

2009 - 2011: Master of Physical Chemistry, Hue University of Sciences, Viet Nam

2015 - now: PhD student in Sedimentology/Encvironmental Geoscience, Geoscience and Geography, Georg-August Göttingen University, Germany

3. International conference contributions

Poster presentation

Nguyen, T. P., Ruppert, H., Sauer, B. (2016). A review of a status of heavy metal contamination in Paddy Field in Vietnam. In: Book of Abstracts of the 9th GeoSymposium of Young Researchers Silesia 2016, Kroczyce, Poland, p. 92 (ISBN 978-83-934005-9-1).

Nguyen, T. P., Ruppert, H., Pasold, T., Fahlbusch, W., Sauer, B., (2018). The transfer of critical elements from soils to rice grains in the Mekong River delta area, Vietnam". EGU General Assembly 2018, Vienna, Austria. EGU2018-4709.

4. Working experience

2009 - now: Lecturer at Faculty of Land Resources and Agricultural Environment, Hue University of Agriculture and Forestry

5. Publication

Nguyen, T. P., Ruppert, H., Sauer, B., & Pasold, T. (2019). Harmful and nutrient elements in paddy soils and their transfer into rice grains (Oryza sativa) along two river systems in northern and central Vietnam. *Environmental Geochemistry and Health*, pp. 1-17. https://doi.org/10.1007/s10653-019-00333-32012.

Nguyen, T. P., Ruppert, H., Sauer, B., & Pasold, T. (2019). Paddy soil geochemistry, uptake of trace elements by rice grains (Oryza sativa), and resulting in health risks in the Mekong River Delta, Vietnam. *Environmental Geochemistry and Health.* Submitted manuscript in a state of “minor revision”.

Nguyen, T. P., Ruppert, H., Sauer, B., & Pasold, T. (2019). Transfer of nutrient and toxic elements from paddy soils into rice plant parts (Oryza sativa) in Vietnam and health risk assessments for the population. *Environmental Science and Pollution Research.* Submitted manuscript in a state of “under reviewing”.

6. Scholarship awarded

- Vietnamese Overseas Scholarship Program
- Geo-Gender-Chancenfonds of Faculty Geoscience and Geography: Conference and Research
- Support of University Federation (Unibund) of Georg-August-University Göttingen (German education).